A STUDY OF GAS EMISSIONS FROM DRY TOILETS

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Degree Programme of Environmental Engineering
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FOREWORD

This thesis work is one of the studies under a sub group, water and sanitation, of the energy and environmental engineering learning team (EE learning team).

Opi enempi (learn more) – project is a development project of Tampere University of Applied Sciences to invest in new facilities for renewable energy and environmental technology, and it is funded by the European Regional Development Fund. Under this project, a learning team for energy and environmental engineering (EE learning team) was formed by students and teachers from both engineering programmes. The aim of this student-based learning team is to learn new ideas and solutions in practice and enhance team-working ability, in order to prepare the students for working life.

This thesis work was supervised by a senior lecturer of the Environmental Engineering study programme, Hilda Szabo**.**

ABSTRACT

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Composting the human excreta in a dry-toilet is a widely applied procedure for stabilizing its organic matter content. A proper water balance in compost is an essential element in maintaining the microbial activity in the compost-mixture, and the moisture content of the compost can be significantly decreased by too intensive ventilation, which affects directly the composting performance. . The inevitable gas emission from the dry toilet, which indirectly reflects the composting process, is another important concern. Also, due to evaporation and aeration of the composting tank, precious nutrients, mainly ammonia-N, can be lost.

The main aim of the study was to understand the composting process from the gas emissions of the excreta. Two dry toilet models were used: Naturum, where urine is separated from the faecal matter, and the Dual-layer dry toilet, which is a mixed composter. The monitoring time of three months was divided into four periods, regarding the adjustments of air ventilation and moisture content. The scope of the work was to evaluate the CO_2, O_2, H_2S, NH_3 and CH_4 emissions, temperature and relative humidity from the composting, and also to optimize the air exchange and consequently the composting process.

From the results it can be concluded that the moisture content of the compost was successfully improved by reducing air ventilation. In the Dual-layer dry toilet, all gas emissions followed the same pattern as the moisture content. However, the moisture content difference was rather small; therefore, a final conclusion about the relationship between the moisture content of compost and the emission rate of gases cannot be drawn. In addition, the composting performance of the Naturum toilet tended to be better than in the Dual-layer dry toilet because of a higher moisture content and smaller composting scale. The input faecal nitrogen loss from the Naturum was also smaller than in the Dual-layer dry toilet. The Dual-layer dry toilet had a problem with increasing compaction of anaerobic volume in the middle part, which affects the composting performance.

The cumulative emission of the gases in the 3-month monitoring time was calculated. For the Dual-layer dry toilet, the cumulative emissions in the four periods were $2.9g \pm 28mg$ for H_2S, $2508g \pm 20g$ for CH_4, and in the last three periods $12g \pm 193mg$ for NH_3. In Naturum, only the H_2S emissions could be quantified, being about $418 \pm 148mg$ over the 3-months. The recommended parameters for both toilets were a moisture content of 35-40%, and an air ventilation rate of 5L/s for the Dual-layer dry toilet and 2-3L/s for the Naturum respectively.

Key words: air ventilation, dry toilet, moisture, NH_3, composting.

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ABBREVIATIONS AND TERMS

C/N ratio	Carbon-Nitrogen ratio
F/S	Faecal-Sawdust ratio
H_2S	Hydrogen Sulphide
IR	Infrared
K	Potassium
N	Nitrogen
$NH_3(g)$	Ammonia
$NH_4^+(aq)$	Ammonium ion
O_2	Oxygen
P	Phosphorus
ppm	Part per million
RH	Relative humidity
TAMK	Tampere University of Applied Sciences
TKN	Total Kjeldahl Nitrogen
UDDT	Urine-diverting dry toilet
UMDT	Urine-mixed dry toilet

1 INTRODUCTION

Aerobic composting is the most favorable method for treating the human waste (feces and urine) in a dry toilet system. Organic fertilizer or soil enrichment material, rich in N, P and K, is the end-product of aerobic biodegradation of feces using sawdust as bulking material (Huuhtanen and Laukkanen, 2006). In other words, quality of compost is based 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 (Szanto G.L. et al., 2006; Sanchez-Monedero, 2000; Hotta and Funamizu, 2006) under different environmental conditions.

As it has be indicated by plentiful studies, the most important factors to function the dry toilet is to keep control of water balance, temperature, nutrients (C/N ratio), as well as pH of the toilet compost in a proper range, as those parameters affect directly or indirectly to the biodegradation performance, resulting in different compost qualities (Jenkins, 1999; Lopez Zavala and Funamizu, 2006.).

Numerous researches and studies have been conducted on the characteristics of aerobic composting of human feces from different impact factors, to explain the process of biodegradation in laboratory-scale experiment. However, in most of these studies, only effects from 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 is to examine the gas emissions from the humanure composting under a real condition, using an automatic gas control system and manual gas detector. Monitoring gases of O_2, NH_3, NH_4, CO_2, together with relative humidity and air temperature will be conducted and observed in 3-month time, in order to follow the continuous composting process. Furthermore, the study result can be a good reference for manufacturing, to improve the toilet design based on operation performance and compost quality, and also provide data for individual who is planning to operate dry toilet for public use.

1.1 Statement of Problems

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 bacteria.

Different from batch-test study, the study environment of this research represents the actual condition, in which some of the factors cannot be controlled or adjusted, for example turning of the compost, using frequency of the toilets, control of temperature, water content, and organic loading (F/S ratio), etc.

The aim of this study is to optimize the functioning of the toilets. This would improve the compost's quality, such as nitrogen rich soil enrichment or fertilizer, as a final end product in the practical condition after stabilization. To obtain high quality compost, it is necessary to understand the process involved as well as to evaluate the most suitable performance conditions. Collecting gas data from air would be a practical method to do that. Additionally, optimum moisture of compost would be estimated and controlled in this study, with the correlation of variable-frequency-driven (VFD) ventilator. The management is challenging, because, beside the aim of advanced biodegradation of faeces, the problems of odour and anaerobic emissions need also to be considered (Lopez Zavala and Funamizu, 2006).

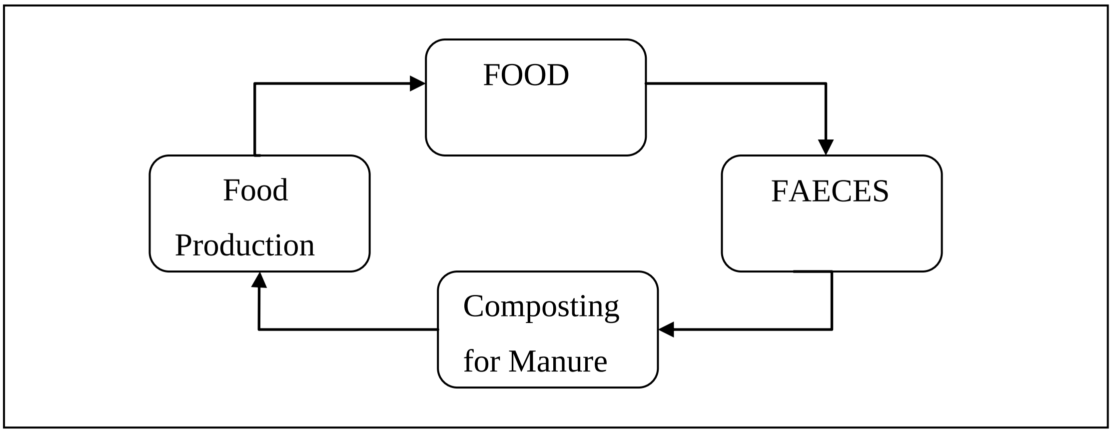
2 DRY TOILET & COMPOSTING

2.1 Dry Toilet

Dry toilet uses no water or uses only small amount of water for operation. It is mainly divided into urine-diverting dry toilet system which separates urine from faeces and urine-mixed system. According to different environmental limitations, dry toilet with small scale may only provide a humanure collection device in which humanure is deposited and then removed to a separate composting location. If there is enough space, a composter can be installed straight under the dry toilet sit and provides on-site composting treatment.

Clean water is one of the most precious resources in the world, and the objectives of using dry toilet is to save water and maintain sustainable lifestyle, without creating pollutions and wasting soil nutrient. Therefore, use of dry toilet becomes a long-term sanitary solution of human disposal for developing countries, especially in regions and areas where there is lack of water supply, to improve public health (Huuhtanen and Laukkanen, 2006).

Composting is the main biological activity in the operation process, with microorganisms and bacteria. Faecal matter and urine cannot be decomposed along without adding lignocellulosic materials, sawdust for instance, which helps to maintain a good C/N ratio. The end products from dry toilet, urine and humanure compost, can be used for soil enrichment materials and fertilisers, which help to close the human nutrient cycle (Huuhtanen and Laukkanene, 2006), as shown in Picture 1.



PICTURE 1. The principle of nutrient cycle (Huuhtanen and Laukkanene 2006, modified)

2.2 Composition of Human Excreta

Human excreta consist of faecal material and urine. Composition of human urine and faeces varies from person to person and from region to region depending on different diets, and environmental conditions. The major valuable compositions of both urine and faeces are N, P and K. Urine contains more nitrogen than faeces because urea and ammonia in urine contributes 88-97% of the total nitrogen in urine (Fittschen and Hahn, 1998). Faecal matter containing 40-55% of carbon (Jenkins, 1999) is on the other hand the main carbon source for the microorganisms found in the compos material of human excreta.

2.3 Aerobic Composting

Aerobic composting is a natural biological process, with the supply of oxygen, to transform the organic matter (carbon source) into soil material (compost). The composting performance depends on the biodegradation rate, being affected by many factors. Such as: the type and quantity of microorganisms, availability and degradability of substrate, availability of nutrients (N, P, K for instance), as well as the environmental conditions (moisture, oxygen supply, pH, temperature. (Lopez Zavala and Funamizu, 2003; Jenkins, 1999) Proper controlling of these parameters provides a suitable environment for microbes and bacteria in compost for functioning.

Since composting is a biological process, compost bacteria combine carbon with oxygen to produce CO_2 and energy (heat). Bacteria are usually divided into several classes, based upon the temperature at which they grow best. Mesophilic bacteria (mesophiles) lives at medium temperature of 20-45℃ (68-113°F), and include human pathogen, whereas thermophilic bacteria (thermophiles) thrives above 45℃ (113°F). In addition, composting process itself has four stages, corresponding to different temperature transformations are taking place on. These phases are 1) the mesophilic phase; 2) the thermophilic phase; 3) the cooling phase; and 4) the curing phase. Humanure contains pathogens that have to be killed during composting process to ensure safety. Lopez Zavala et al. (2004) evaluated the temperature effect on aerobic biodegradation of faeces using sawdust as matrix, and they suggested that the optimum temperature of faeces biodegradability is about 60℃, which is within the thermophilic range. Pathogens, however, only have a limited life time outside human body, and given enough time for curing phase, they will die even in low-temperature compost (Jenkins, 1999). Temperature, an environmental factor, is therefore playing an important role, which affects microbial growth and biological reactions of the whole process.

2.4 Possible Gas Emission

CO_2 emission is expected in the composting process due to the breaking down of organic faecal matter. NH_3 and N_2O emissions occur are due to nitrification and denitrification processes (Szanto G.L. et al., 2006). CH_4 is a greenhouse gas and it is produced under anaerobic condition with absence of oxygen. H_2S is another major odorous gas produced during composting that forms under anaerobic conditions. It is produced due to the bacterial reduction of sulphate and decomposition of sulphur-containing organic constituents (Arogo et al., 2000).

2.4.1 Inhibition of Ammonification

There were a lot of studies investigating the nitrogen transformation, nitrogen loss, and the nitrogen recovery rate of composting. In most of these studies sawdust was used as bulking material and variety of individual variables and experimental conditions were taken into account (Sánchez-Monedero et al., 2000; Hotta and Funamizu, 2006c; Hotta and Funamizu, 2007; Bai and Wang, 2011). Nitrogen loss in the form of NH_3 was found to be more than 90% (Lopez Zavala and Funamizu, 2006). The major outcome of these studies was to prevent N-loss of the compost is the inhibition of the ammonification. The factors that influence on the ammonification process are:

Composting temperature

Under mesophilic condition, higher input faecal nitrogen loss (31.4%) was obtained comparing with thermophilic condition (17%). Reason for this is that mild temperature is more favourable for ammonifying-bacteria to survive (Bai and Wang, 2011).

Dry toilet type

Urine contains certain amount of urea, and which is the main nitrogen source. However urea is unstable in the sawdust matrix, especially when faeces are mixed with urine. Hotta and Funamizu (2006a) conducted a batch test to compare the faecal nitrogen recovery rate with urine-diverting dry toilet and conventional style in which faeces and urine were treated in the same composter without separation, and the result showed that more than 90% of input nitrogen might be maintained for UDDT, while less than 5% for conventional CMDT.

The explanation lies in the fact that faeces contain several urease-producing bacteria and urease is an enzyme that catalyzes the hydrolysis of urea into CO_2 and NH_3, resulting in nitrogen loss (Suzuki et al., 1979 cited in Shinya and Funamizu, 2006b). It is, therefore assumed that urine-diverting dry toilet could minimize the urea hydrolysis (ammonification) for input nitrogen loss.

C/N ratio

Low C/N ratio which means N is in excess, and carbon is being limiting instead. The microorganisms cannot use all the N and the excess is lost as NH_3. If there is not enough N-input, composting becomes slow and will not heat up. A good C/N ratio for a compost is suggested between 20/1 and 31/1 (Jenkins, 1999).

pH

Another factor affecting the magnitude of volatilization is pH. Gaseous NH_3 and aqueous NH_4^+ are in equilibrium at a pH about 9. The higher pH may 'forces' more NH_4^+ into NH3. In practical operation of composting system, however, there is insignificant evidence to manually adjust pH for improving great composting performance. (Cornell composting, 1996)

2.5 Moisture Content

Proper water balance of the toilet matrix, same as temperature, is an important factor for operating a dry toilet which affects the material and compost properties, as well as microbial activity (Tanaka et al., 2009). Composted materials shrink incredibly (40-80%) mostly because of water loss, and consequently the compost gets dry (Jenkins, 1999).

The recommended optimum moisture contents vary widely from 40%-65%, to achieve both nitrogen content conservation and proper biodegradation rate (Lopez Zavala and Funamizu 2006; Bueno et al., 2007). Lopez Zavala and Funamizu (2005) conducted a research about different phenomena in compost depending on the moisture content, and indicated that moisture content of 65% is a critical level, which should not get over in order to ensure aerobic degradation of faeces. High moisture content (> 65%) causes both aerobic and anaerobic decomposition, resulting in problems of odours, anaerobic emissions, nitrite formation, as well as increase of sulphate concentrations. The excess moisture increase film thickness and fill the smaller pores between particles, limiting oxygen transport. In opposite, low moisture condition can restrict the movement of bacteria (Cornell composting, 1996).Therefore, moisture content at about 50%-60% or little higher is recommended (Lopez Zavala and Funamizu, 2006). Additionally, according to Bueno et al. (2007), the moisture content influences mostly on the organic matter content of the compost and N-loss.

3 DRY TOILET MODELS

Both toilets 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). The Dual-layer dry toilet is the first trial composting toilet with the biggest composter among other products of BIOLAN Oy.. Both toilets were installed indoors and got used in the laboratory building at TAMK since 9th January 2011, at the same time of the opening of the new laboratory building. Neither of them has been emptied yet, excluding the separated urine tank of Naturum. The Dual-layer dry toilet was installed at the first floor and its composter was installed at the basement, while Naturum was installed one floor right up on top of Dual-layer dry toilet, together with a waterless urinal.

3.1 Dual-layer Dry Toilet – Urine-mixed System

Based on the composting temperatures generated from the dry toilet's compost, the toilet systems are grouped into thermophilic compost (above 45℃) and mesophilic compost (below 45℃). Dual-layer dry toilet is a mesophilic dry toilet, which has average temperature of slightly over 20℃.

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This is a urine-mixed composting toilet, 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). Like other normal dry toilets, adding some clean organic cover materials is important in particular to eliminate odour. BIOLAN peat was employed to be the bulking material for balancing the C/N ratio.

The toilet seat on the first floor is connected with the 400L composter underneath at the basement. 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 2).

PICTURE 2. Dual-layer dry-toilet composter (Right) with Naturum urine tank (left) and gas control system (back) at the basement (Photo: Pui Ki Tsang 2012)

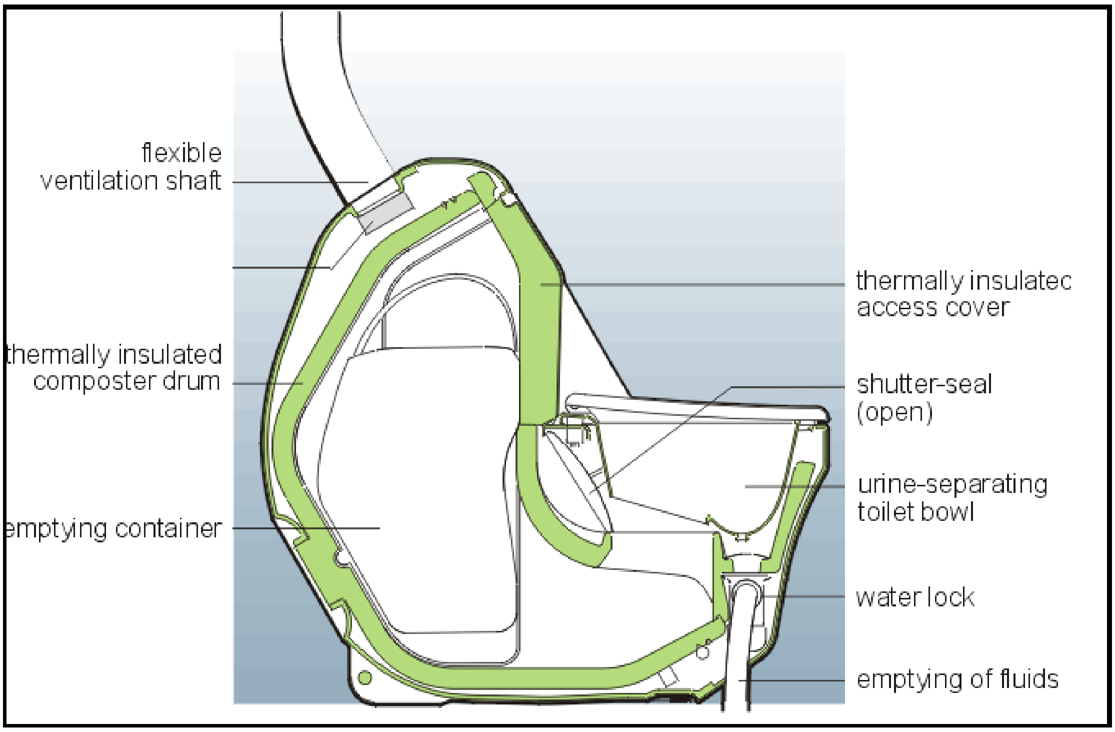
Because of its large composting capacity, this passive and low-temperature composting with low-maintenance requirement is expected to yield relatively pathogen-free compost after a period of time.

3.2 Naturum – Urine-diverted System

The key part of Naturum 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. The approximate dimensions of the toilet itself, excluding the urine container, are 83cm x 80 cm x 80cm (Picture 3). The composting space at the back is 30 litres and the emptying container is 10 litres (Biolan Oy, 2010).


PICTURE 3. Naturum's front view (Photo:Pui Ki Tsang 2012)

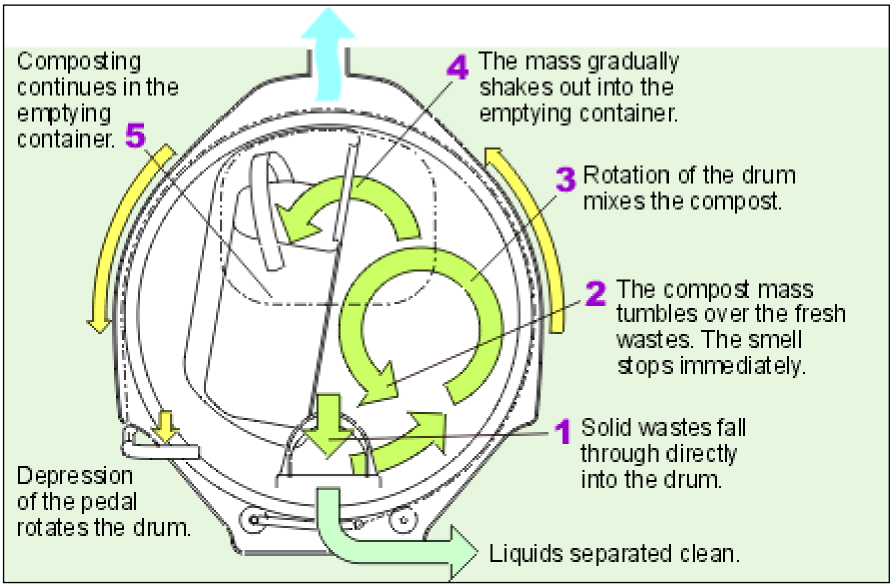
Besides the rotary drum composter and the emptying container, the other compartments of the toilets are ventilation shaft, thermal insulator, foot pedal, toilet bowl, shutter-seal, etc. (Picture 4).



PICTURE 4. Side view of Naturum (Biolan Oy, 2010)

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 (Picture 4). 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 (Biolan Oy., 2010). The handle on the right side is to control the opening of the faecal hole.

Urine, in this case, 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 and blocking of the pipe.



PICTURE 5. Drum composter operation-Naturum (Biolan Oy, 2010)

The specific bulking material of Naturum is a dark green granule with tiny granular texture. Since the composting space is limited, the use of a particular bulking material should be as effective as possible. The amount of Naturum bulking materials required is only half amount of the normal ground peat, which is normally used in dry toilet. The coarse texture of the granule keeps the compost mass airy and intensifies the composting process (Picture 6). 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).

In addition, Naturum only had 9 using times per month in average which is much less than the Dual-layer dry toilet. Moreover, Naturum is a urine-diverting dry toilet, and there were roughly only 2.5 using times per month of faecal input, according to the user record.

PICTURE 6. Naturum bulking material
(Photo:Pui Ki Tsang,2012)

4 METHOD & MEASUREMENT

4.1 Measurement Schedule

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. Since proper water amount enhances the movement of bacteria and therefore is important for the microbial activities. 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.

TABBLE 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 toilets

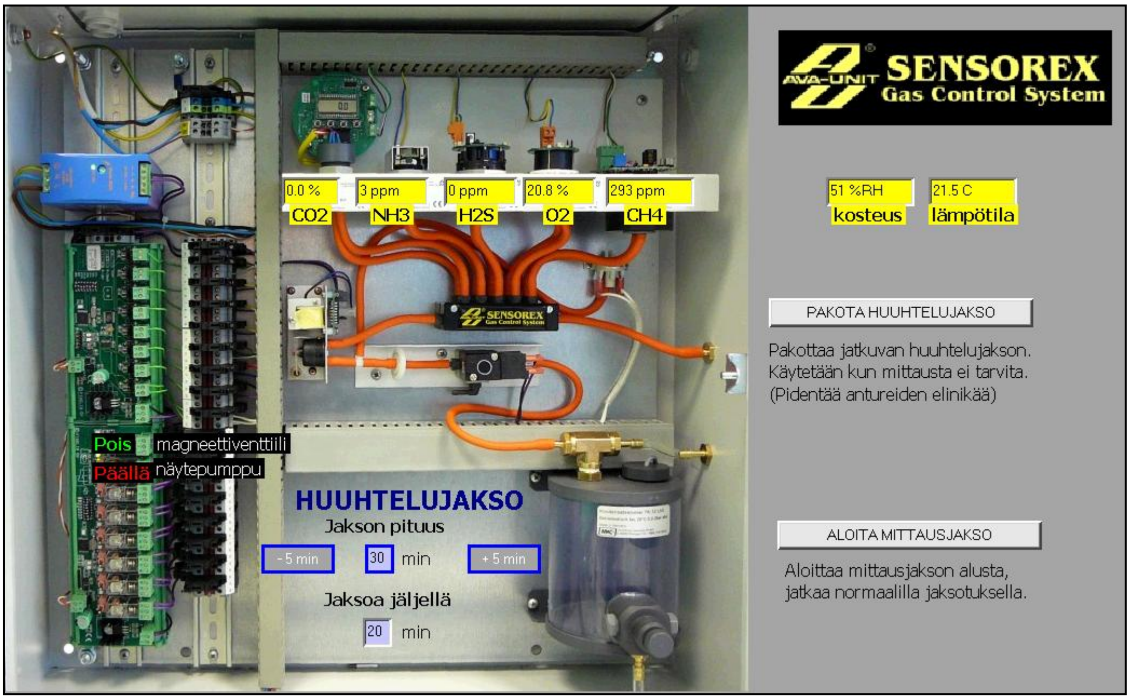
4.2 Measurement of Gas Emission

4.2.1 Sensorex Gas Control System – Dual-layer Dry Toilet

The gas control system, 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 (℃). The data sheet of the sensors, for example the measuring range, can be found from appendix Ⅰ. The expected life expectancies of the sensors are two years with continuous use, and rinsing which takes clean air into the system to 'wash' the sensors, is an important maintenance for the system. Therefore rinsing has to be taken place when measurements are not required (Sensorex Oy., 2011).

The physical measuring devices and sensors are located at the basement near the composter (Picture 2). The tube for taking gas samples and the sensor for humidity and temperature were installed independently at the ventilation pipe of the composter. Two separated holes were drilled at the ventilation pipe to place the sensor and tube inside. In order to protect the gas control system, a cotton layer was placed at the head of the tube and a filter was inserted in the system, to lower the damages to the sensors due to moisture.

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 7). 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.



PICTURE 7. Control panel of Sensorex gas control system (Photo: Pui Ki Tsang, 2012)

4.2.2 Manual Gas Analyze Device - Naturum Dry Toilet

Manual gas measurement 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.

4.3 Measurement of Air Flow

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.

4.3.1 Air Ventilation System

The Air ventilation system of the dry toilets are joined together and linked to the variable-frequency-driven (VFD) ventilator at the building's rooftop, but it is an independent ventilation system apart from the rest of the building. Two toilet rooms and the basement room are jointly ventilated with another VFD ventilator, which is also at the rooftop. The detail ventilation map can be found from Appendix Ⅱ.

The air flow conditions of toilets got affected at the same time when the air ventilation adjustment once was done at the VFD.

4.3.2 Air Flow Measuring Device

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.

4.4 Moisture Control

The determination of moisture content of the compost was done according to the Finnish Standard SFS-EN 13040, with moisture analyser XM 60 under drying temperature 103 ℃. 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. Also, adding proper moisture to the compost was to prevent premature drying and incomplete stabilization. On the other hand, extra water had not added to Naturum since it got a satisfied water content value already after the reduction of air ventilation.

4.5 Total Kjeldahl Nitrogen (TKN) Analysis

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.

Three samples with replicates and blanks (a preliminary analysis omitting only the sample to provide reference point for comparison) were first taken to the Büchi Digest System K-437 in 370℃ for a preliminary digestion to convert the organic nitrogen to ammonia. Then the digestion tubes were brought to the Büchi Distillation Unit K-314 for distillation, so the ammonia would be collected in boric acid absorbing solution. Followed by titration to determine the consumption of sulphuric acid, the % of TKN can be found with calculation (Hoegger, 1998).

4.6 Calculation of the Mass of Gases Eliminated through Ventilation

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]= 0.821 $\frac{\mathrm{L\,atm}}{\mathrm{mol\,K}}$
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

The amount of gas 'n' given in mol/time was than transformed into mass unit mg/time by using formula: $m = n \times M$, where 'M' is the molar mass (g/mol) of the particular gas.

4.6.1 Statistical Method - Standard Error Calculation

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.

5 RESULTS

5.1 Reduction of Air flow and Increase of Moisture

It was assumed that the composts of the dry toilets were too dry due to the significant air ventilation. In the Dual-layer dry toilet, compost from the bottom layer had been composted for a year since the toilet was installed.

Most of the users of Dual-layer dry toilet commented that they felt a breeze when sitting on the toilet. The air flow measurements were conducted before and after to get the right air exchange level in the second period and the data is shown in Table 2.

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	Moisture Content		
	(L/s)	(%)		
1	4.5	40		
2	3	64		
3	3	77		
4	3	46		

The VFD ventilator was adjusted to a level of 10L/s and the air ventilation rates were significantly reduced by more than 80% and 30% of the original values of Dual-layer dry-toilet and Naturum respectively. 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. 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 2).

5.2 Gas Compositions and Emissions

Continuous measurements of gas emissions, RH and air temperature in four periods were carried out using the Sensorex gas control system for Dual-layer dry-toilet. The sensor of NH_3 in the system was not operating accurately in the first period and it was calibrated in the second period.

The measurements of Naturum were done with the MX6iBird manual gas detector, but it did not measure NH_3. The measurement work of Naturum became limited due to the restraints of measuring device, and because the toilet could not be accessed during the school holiday.

TABLE 3. Average gas concentration

	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

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 the 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. 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, which also took the air flow factor into account. The emission rates were calculated according to the description in section 4.6, from the average gas concentrations (Table 3) and the measured air flow rates (Table 2).

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	1.0×10^{-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	1.0×10^{-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℃, 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 (0.1mg/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.

The cumulative emissions of the gases in the 3 month monitoring time were calculated with the data in Table 3. For Dual-layer dry toilet, the cumulative emissions in four periods are 2.9g $\pm$ 28mg for H_2S, 2508g $\pm$ 20g for CH_4, and in last three periods 12g $\pm$ 193mg for NH_3. For Naturum, only the H_2S emissions could be quantified, being about 418mg $\pm$ 148mg in a 3 month time.

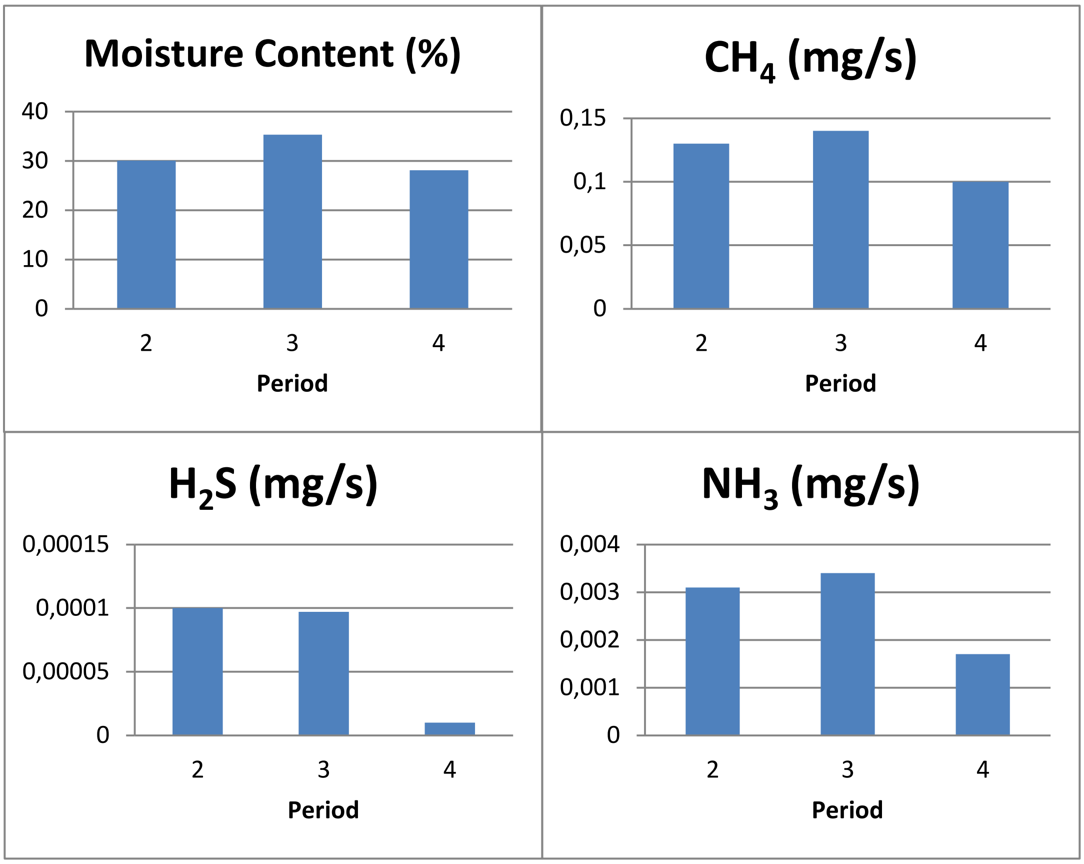


FIGURE 1. Gas emissions and moisture content from the second to third period (Dual-layer toilet)

Figure 1 above is a graphical presentation of the gas emission rates (Table 4) and the water balance of the compost (Table 2), consisting of the data of moisture content, CH_4, NH_3 and H_2S from Dual-layer dry toilet. In the first period, the ventilation was about 30L/s and the highest emissions of CH_4 and H_2S were obtained as well. However, data from that period is not a comparable reference to compare the gas emissions from the rest of the period because of the air flow rate difference, applying the same to Naturum. During the second, third and fourth period the ventilation was constant, therefore the effect of moisture content of the compost on the gas emissions can theoretically be assessed. Considering the second period to the fourth period, the emissions of the gases tended to drop with an increase in the moisture content. In the third period, CH_4 and NH_3 had the greatest emissions with the highest moisture content. In the last period, all gases dropped along with moisture content, especially for H_2S emission.

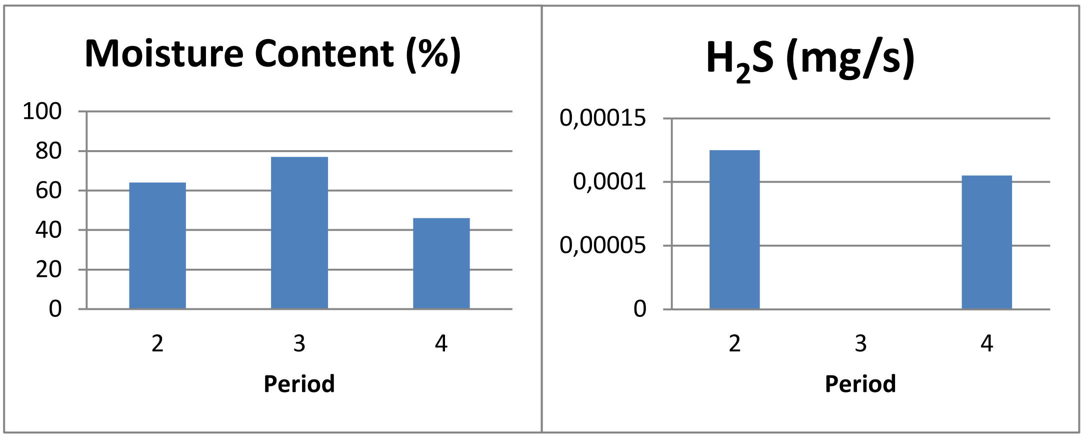


FIGURE 2. Moisture Content and H_2S emission rate from the second to third period (Naturum)

Moisture content in Naturum remained higher than in Dual-layer dry toilet (Figure 2). The highest H_2S emission obtained was in the second period with the second-highest moisture comparing to the other periods.

5.3 Total Kjeldahl Nitrogen (TKN) Determination

The analysis was done in the second period. Compost samples were taken from Naturum and the upper and the lower parts of Dual-layer dry toilet. Compost from Naturum contained about 1.37% mass of N (TN). 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.

6 DISCUSSION

6.1 Anaerobic Compaction in Dual-layer Dry Toilet

Sufficient oxygen was steadily supplied to the compost due to the force ventilation system, therefore aerobic composting process was expected. The low CO_2 level inside the composter however 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). 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.

6.2 Air ventilation affects Moisture Content

In the first period, the daily water loadings of the dry toilets were smaller than the evaporation rate, resulting in low moisture content of the compost, especially under the forced ventilation. The air ventilation directly affected the relative humidity of air and consequently improved the moisture content of the composts. However, the moisture content of the compost from both toilets dropped in the last period although the RH levels remained high (Table 3). This is explained because of the dry toilets not being in use for the last observation period. In order to maintain optimal moisture levels, regular use of the toilets is important.

In Naturum, the moisture content was higher than in Dual-layer dry toilet. Naturum is a UDDT system, meaning that faeces are composted with bulking material only. The moisture content of Naturum increased up to 77% in the third period without the addition of water (Table 3). The reason for this is that the composting size of Naturum is small and also, it has a tight-designed composter and bulking material with high moisture content (> 90%).

Attention has to be paid to the adjustment of indoor air ventilation since there can be a large difference between the need for aeration of the dry toilet and that of the rest of the building. Odour problems might occur when the air exchange in the toilet is adjusted to be optimum, which happened once in the third period.

6.3 Moisture content and Patterns of Gas Emissions

Because of the strong ventilation, the moisture content of the compost in Dual-layer dry toilet is low and as seen in Table 1, the emission rates of gases were high in general in the same period. Therefore, it is believed that high ventilation rate leads to high gas emissions. 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.

Naturum compost presented a bit different H_2S emission patterns with moisture content. 0 H_2S emission was obtained in the third period with the highest moisture content among other periods.

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.

6.4 Biodegradation Rate

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 (Figure 1). 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, S. 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 the aerobic composting process was in action. 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.

6.5 NH_3 Emission and the N-value of the Compost

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 UMDT system tends to have a greater nitrogen loss than in UDDT system which agrees with the urea hydrolysis of Hotta and Funamizu (2006a). However, the TN value in both composts is still relatively low (< 3%). (Bueno et al., 2007)

N is lost because of ammonification and therefore 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.

6.6 Combustible Gas and Safety

CH_4, H_2S and NH_3 are flammable gases which have explosive potential under certain concentration in air if there is an ignition source. It is recommended to keep the concentration under 25% of the lower explosive limit (LEL) to ensure safety. (The Engineering ToolBox, n.d.) In this case, the emission concentrations of the flammable gases emitted from the dry toilets were all under the 25% of LEL. There is no momentous problem concerning the potential explosion because of the high concentration of the flammable gases.

6.7 Evaluation of the Sensorex Gas Control System

The Sensorex gas control system is a good tool to monitor the gas emissions in general. However, regarding gas quantity and composition it is not the best tool for study purposes. The sensors are possibly not sensitive enough to detect gases of low concentrations. For example, it does not detect the low atmospheric concentration of CO_2. The gas data recording system was not able to show a responding measurement time in the history review that the time changed every time according to the login time of the system. In addition, the pump occasionally stopped during the first few periods due to technical concerns, but the recording system could not indicate when measurement had not taken place. Therefore, correct data extraction was difficult.

6.8 People's Attitude of Using Dry Toilet

Developed countries have a long history of using flushing toilets. Faeces and urine are seen as unpleasant and are kept away from. Unwanted matter is flushed out of sight and mind.

Finland is a developed country and the population is generally well-educated. The concept of using dry toilet has been introduced a long time ago. However, people's attitudes towards dry toilets are not positive, at least in the light of this research and the low frequency of using the dry toilets. The two dry toilets were installed next to water-saving flushing toilets which are divided into female and male. Students attend regularly laboratory classes and staffs have offices near the bio-toilets. This group of people have been introduced to the toilets and have received instructions in how to use them and the benefits gained from dry toilets. However, after one and a half years of installation, people still tend to prefer the use of flushing toilets though bio-toilets are just as accessible.

The use of dry toilets has been promoted to developing countries. Low educational levels, cultural problems, religion and psychological factors have been obstacles for future developing work.

According to results of this study, teachers and students alike show low interest of using dry toilet. It is possible that due to cultural difficulties it is difficult to accept the unusual concept of treating human waste, also for people from developed countries. Since only a small group of people are involved, no general conclusions can be drawn. However, it would be an interesting topic to further investigate people's opinions in a cultural or physiological sense, even in developed countries.

7 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 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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APPENDICES

Appendix Ⅰ Measuring limit of Sensorex gas control system

Sensorex Oy.,2011. Sensorex käymäläkaasujen Näytteenottojärjestelmän Toiminta ja Käyttö

1. Anturit

Järjestelmään kuuluu viisi kaasuanturia ja kanavaan asennettava yhdistetty lämpötila- ja kosteusanturi.

Anturi 101, Hiilidioksidi (CO_2)
Tyyppi: SX-303DM
Mitta-alue: 0-5%

Anturi 102, Ammoniakki (NH_3)
Tyyppi: SX-200SE
Mitta-alue: 0-100ppm

Anturi 103, Rikkivety (H_2S)
Tyyppi: SX-200
Mitta-alue: 0-20ppm

Anturi 104, Happi (O_2)
Tyyppi: SX-200
Mitta-alue: 0-25%

Anturi 105, Metaani (CH_4)
Tyyppi: SX-303DM
Mitta-alue: 0-5%

Anturi 106, Suhteellinen kosteus (RH)
Tyyppi: KLK-100
Mitta-alue: 0-100 %RH

Anturi 101, Lämpötila (°C)
Tyyppi: KLK-100
Mitta-alue: -50…+50 °C

Appendix Ⅱ Air Ventilation map of the Dry toilets' compartment

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