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Co-composting of Kitchen Waste, Faeces and Sewage Sludge as Sustainable Strategy for Island Waste Management: Process Dynamics

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ABSTRACT

Solid waste management is an inevitable challenge for Chinese government during the island construction practice in the South China Sea. Composting, if it is properly put into application, can constitute an environment friendly and sustainable method for solid waste management on these newly-built artificial coral reefs, due to its great potential to improve coral sand soil with low cost. As the key components of island solid wastes, kitchen waste, faeces and sewage sludge were combined in ratio of 1:1:1, which conformed to the actual production and constituted a mixed waste system. Thus, using a self-made intelligent reactor, this paper presented the performance and potential of mixed treatment of kitchen waste, faeces and sewage sludge through co-composting with the co-amendment of sawdust and cornstalk. A series of process parameters were monitored, the laws about degradation and resynthesis of organic matter, transformation and loss of nitrogen were revealed in this paper. The results indicated that applying the aerobic composting technology to the solid waste treatment in the mixed system of kitchen waste, faeces and sewage sludge with co-amendment of sawdust and cornstalk was feasible, and the optimal mixed ratio of total waste to co-amendment was 4:1 on analysis of technique and economics.

INTRODUCTION

In recent years, sea enclosing and land reclamation has become an effective method in China to accommodate the increasing need of space for living and development (Wang et al. 2014). The Chinese authorities have carried out a series of island expansion projects with sophisticated techniques in the South China Sea, thus, a number of artificial extended coral islands have been initially formed, such as Mischief Reef, Subi Reef and so on. However, with the requirement of the exploitation and defence in these remote islands, a population boom will be foreseeable and the production of solid waste will grow dramatically. Island urbanization can always cause many related problems, such as environmental pollution, obstructions to natural ecological processes and so on (Ledee et al. 2008, Lin et al. 2013). A field investigation found that island solid waste is featured by high content of organic compounds (up to 60%), which is mainly composed of kitchen waste, faeces in the septic tank and sludge from sewage treatment facilities, and the average daily production of each waste is approximately equivalent. Besides, the surface soil of these islands is made out of coral sand originated from sea-bed sediment via a type of large sand pumping vessel. Compared with normal soil, it exhibits unsatisfactory characteristics because of poor physicochemical properties and low nutrient content.

Aerobic composting technology has been widely used in municipal solid waste treatment due to its quick, simple and easy operation (Jara-Samaniego et al. 2017). Compared with other options for solid waste disposal, lower environmental and social costs make aerobic composting a more attractive alternative. Moreover, after the process of composting, most organic fraction would be converted to stable humus, and this final production with an added value can be completely served as soil amendment, bioremediation reagent and direct growing media (Chen et al. 2015), which is expected to provide the corps, lawns, flowers and other plants with necessary nutrients for their growth and development (Jara-Samaniego et al. 2017). Thus, it is really an opportunity to establish a mixed waste system which can perform as a combination of kitchen waste-faeces-sewage sludge. In this way, the main waste streams in the islands could be processed only once with great administrative convenience and low investments. However, information on the process dynamics in co-composting of kitchen waste, faeces, and sewage sludge is lacking, most scientific researches and engineering applications are focused on single system composting or two ingredients co-composting. The advantage of the mixed system is that additional kitchen waste can alleviate the stickiness caused by the single composting of sludge, consequently, the free airspace of the heap is able to aggrandize to a certain extent, for the kitchen waste itself, the problem of excessive salt content is weakened at the same time. Hence, co-composting process of the mixed system of kitchen waste-faeces-sewage sludge has its own particularity and worth the investment. In this study, the authors chose sawdust and cornstalk as composite amendments for the mixed heap. The main objectives were to investigate the co-composting process of kitchen waste, faeces and sewage sludge, demonstrate its feasibility, and determine the most optimal solution of amendment dosage.

MATERIALS AND METHODS

Raw materials: The kitchen waste was collected at the school cafeteria in LEU (Chongqing, China), which was mainly the leftover. The sewage was collected at a domestic sewage treatment plant, which did not contain the industrial waste ingredient. The faecal sludge was taken from a tertiary septic tank beside the student accommodation area. The sawdust and cornstalk were separately taken from a furniture factory and a rural area (Harbin, China). The basic physicochemical properties of the above materials are presented in Table 1.

Composting device: The experiment was carried out through an intelligent aerobic composting reactor (Fig. 1) which was designed by the authors' team. The main fermentor was a cylindrical tank with a total inner height of 58 cm, and it was made of 316 stainless steel. At the initial phase, all the materials occupied 90% the volume of the whole reactor, and the effective volume was 38 L. A layer of 5 cm polyurethane was used as an insulating layer to prevent heat loss. An exhaust hole with an inner diameter of 8 mm was equipped on the top of the fermentation tank, the exhaust gas was introduced into the exhaust gas treatment module which consists of the sulphuric acid and sodium hydroxide solution. The upper lid could be opened from both sides when the materials were input or output. A stirring motor at the top of the reactor was fixed with the holder, which could be slowed down by the reduction gearbox and then spinning the mixing blade at a low speed. Three small sampling ports were equipped on the side of the reactor, two layers of PVC sieve plates with 49 micro vents (Φ2 mm) arranged evenly were fixed at the bottom. The gas distribution space under the sieve plate was used as a leachate collection chamber at the same time, and a leachate discharge pipe (Φ15 mm) controlled by a gate value was set. The intelligent control box could realize the real-time monitoring and feedback of the inside temperature to determine the different stages of the composting process and adjust the ventilation. In addition, the mixing device was controlled to start every two days for 20 min each time (0.2 r/min). An air heating box (20°C~50°C) used to deal with the occurrence of extremely low temperature was equipped after the air compressor, and did not start at normal temperature.

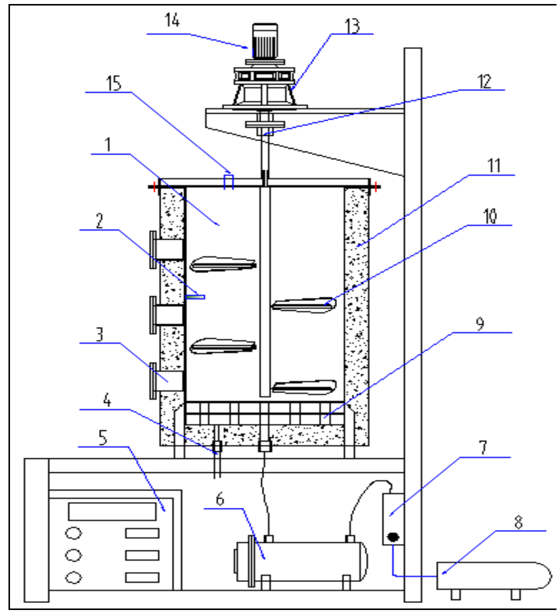

Fig. 1: Main structure of the composting reactor. 1. Fermentation room 2. Temperature probe 3. Sampling opening 4. Leachate collection channel 5. Intelligent control box 6. Air heating box 7. Gas flow meter 8. Air compressor 9. Gas distribution space 10. Mixing blade 11. Polyurethane insulation 12. Coupling 13. Reduction gearbox 14. Stirring motor 15. Exhaust gas collection channel

Experimental design: According to the field investigation and the accounting of insular solid waste, the average daily output of kitchen waste, faeces and sewage sludge was equivalent, and these three kinds of wastes were mixed in a ratio of 1:1:1 at the period of preliminary composting. Although different researchers believed that the most suitable C/N for different composting systems varies, many studies found an optimum C/N between 20 and 40 for most organic solid waste (Sasaki et al. 2008, Guo et al. 2012). Many experiments and engineering applications pursue a high initial C/N, but often at the expense of excessive amendments, which is bound to limit the engineering applications of co-composting in the South China Sea. Moreover, the C/N calculated from the initial raw materials and amendments does not exactly match the actual C/N available to the microorganisms. Considering the initial C/N of materials and the actual situation of the island project, three experiments were designed as mentioned in Table 2. All the heaps were in the same ventilation strategy through continuously forced ventilation, the ventilation of each heap was regulated by the PLC control module, which was 120 L/min in the heating and cooling phases, and 300 L/min in the thermophilic phases (temperature >40°C).

Analytical methods: In the compost samples, MC was determined by the weight loss method after drying the samples for 12 h at 105°C (Bustamante et al. 2008). Total organic matter (TOM) was determined by potassium dichromate volumetric-external heating method, total nitrogen (TN) was determined by semi-micro Kjeldahl method, the NH_4^+-N was determined by the KCL leaching-indophenol blue colorimetry, and the NO_3^--N was determined by NaCl leaching-UV spectrophotometry (Bao 2000). EC (electrical conductivity) and pH were determined by a multi-parameter meter (WTW multi 340i, Weilheim, Germany) in the aqueous extract (compost/deionized water, 1:10, w:v) (Juárez et al. 2015). The E_4/E_6 was determined by DR6000 UV-VIS spectrophotometer (HACH, Loveland, USA). The germination index (GI) was determined by the method of seed germination test with *Lepidium sativum* L. (Zucconi et al. 1981). All indexes were determined in triplicate.

Data processing and analysis methods: The Excel 2013 and Origin Pro 8.5 software package were used for the statistical analysis and plotting, respectively.

RESULTS AND DISCUSSION

Dynamic changes in basic physicochemical parameters: As shown in Fig. 2, a series of parameters, such as temperature, MC, pH and EC were recorded during the co-composting process which lasted for 33 days. Compared with the conventional composting process, the co-composting of KW-FS-SS follows the typical temperature change curve, and all heaps experienced three stages which consisted heating, thermophilic and cooling phases (Fig. 2a). In the initial period, the temperature of composting materials was close to room (28°C). Cooperband (2000) believed that mesophilic bacteria, actinomycetes, fungi and some protozoa were able to grow well at 10°C~45°C, and their metabolism and reproduction depended on the decomposition of sugar and amino acids. Heap 1 and heap 2 reached the thermophilic phase (>45°C) (Gajalakshmi & Abbasi 2008) at the first day and both lasted for 6 days. For the heap 3, the time for entering the thermophilic phase was delayed because of the poor initial properties, it reached the highest temperature at third day and the thermophilic phase lasted for 10 days due to the high waste substrate content. The thermophilic phase was the active stages of composting process, and most organic matter is degraded in this period including refractory lignin. The high temperature duration of reaching more than 55°C went beyond 3 days, hence all heaps achieved the inactivated effect of germs and *Ascaris* eggs and complied with the related Chinese standards (GB7959 2012). After the thermophilic phase, the treatment temperature began to decrease, and all heaps cooled to room temperature 23 days later.

In the condition of initial amendment dosage as designed, no dehydration or hydrating measures were conducted. The MC was increased along with the co-composting process and then decreased for all heaps (Fig. 2b). The MC increases in the first three days for heap 1 and heap 2 was the result of the rapid start of co-composting, but the response

Table 1: Physicochemical characteristics of the raw materials.

Amendments	pH	Moisture Content (%)	Total Organic Matter (TOM) ($g \cdot kg^{-1}$)	Total Nitrogen (TN) ($g \cdot kg^{-1}$)	C/N
Kitchen waste	4.43±0.11	71.8±1.2	871.35±1.96	22.35±1.34	22.61
Faecal sludge	8.19±0.07	83.9±0.8	891.84±2.67	52.67±1.60	9.82
Sewage sludge	6.11±0.10	84.9±0.5	433.93±2.11	28.16±0.46	8.94
Saw dust	-	11.3±0.1	976.64±0.34	6.53±0.22	86.75
Corn stalk	-	9.6±0.2	953.62±0.62	7.56±0.19	73.12

Table 2: Co-composting experiment design under different dosage of amendment

Treatments	Addition[a] KW:FS:SS:SD:CS (kg)	TMW:TMA[b]	TM[c] (kg)	Initial MC[d](%)	Initial C/N
Heap 1	2 : 2 : 2 : 1.5 : 1.5	2 : 1	9.00	56.95	35.60
Heap 2	3 : 3 : 3 : 1.125 : 1.125	4 : 1	11.25	66.25	26.93
Heap 3	4 : 4 : 4 : 1 : 1	6 : 1	14.00	70.20	22.39

[a]KW: kitchen waste, FS: faeces, SS: sewage sludge, SD: saw dust, CS: corn stalk, calculating with wet weight.
[b]TMW: total mass of waste. TMA: total mass of amendment. [c]TM: total mass of the whole heap. [d]MC: moisture content.

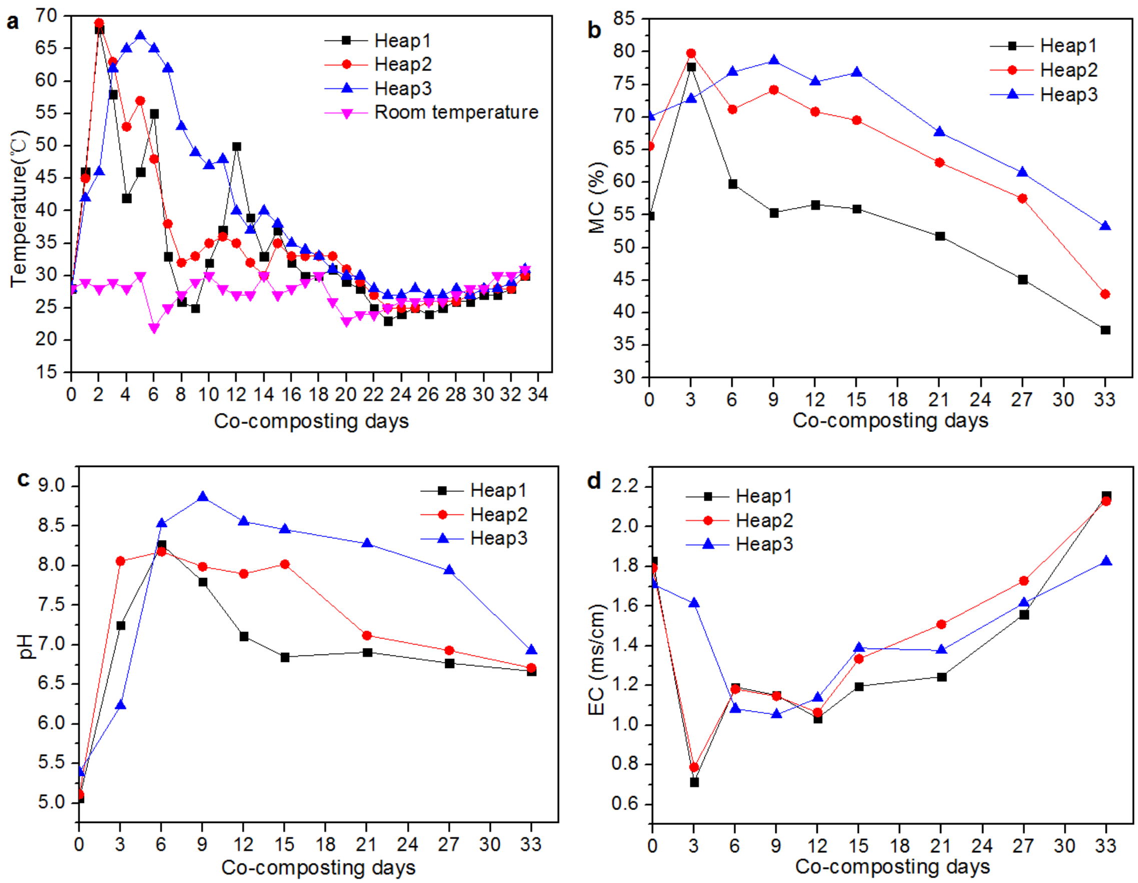

Fig. 2: Dynamic changes in temperature (a), MC (b), pH (c) and EC (d) during co-composting.

for heap 3 was relatively delayed. The results showed that heap 1 and heap 2 had better initial conditions, which providing a good environment for the microorganisms. Most organic substrates susceptible to microbial utilization were rapidly degraded at the early stages of co-composting and produced large amounts of water, which was more than the sum of the water consumed by the microbial life and evaporated by ventilation system, therefore, an obvious MC increase was observed. In the preliminary stages, the extent of MC increase was not evident for heap 3, and the date of reaching the highest value was delayed. The results indicated that the initial MC of 70% could restrain the microbial activities, which was consistent with the temperature trend in Fig. 1a. High MC limited the oxygen transfer and diffusion, and increased the heat capacity of the compost, so that the warming of the heap 3 was slow. This showed that MC could significantly affect the reactor temperature, which was similar to the study results by Zang et al. (2016). In the middle and late stages of co-composting, the microbial activity decreased and the co-composting process entered the cooling phase. The mesophilic microbes have a lower ability to decompose organic wastes than the thermophilic microbes, the MC continued to decline in all heaps.

During the co-composting process of KW-FS-SS, the pH increased rapidly and maintained a high value state for a certain period of time, then decreased slowly and became stable (Fig. 2c), while the EC decreased firstly and increased subsequently (Fig. 2d). The feedstock showed obvious acidic, then a sharp increase in pH was observed in the early stages due to the consumption of small organic acids, which led to the decrease in EC at the same time. As the reaction progressed, the decomposition by microbial activity increased, a large amount of ammonium, fatty acids and mineral salts were formed, resulting in a period of time with high pH and a continued increase in EC. Compared with heap 1 and heap 2, heap 3 reached the highest pH at the ninth day, and a period of pH>8 lasted over 15 days, which may cause an offensive smell and significant nitrogen loss. At the end of co-composting process, the pH of each heap decreased and gradually stabilized, which was mainly due to combined action of the accumulation of organic acids, the conversion of NH_4^+-N to NO_3^--N and the loss of NH_3. As

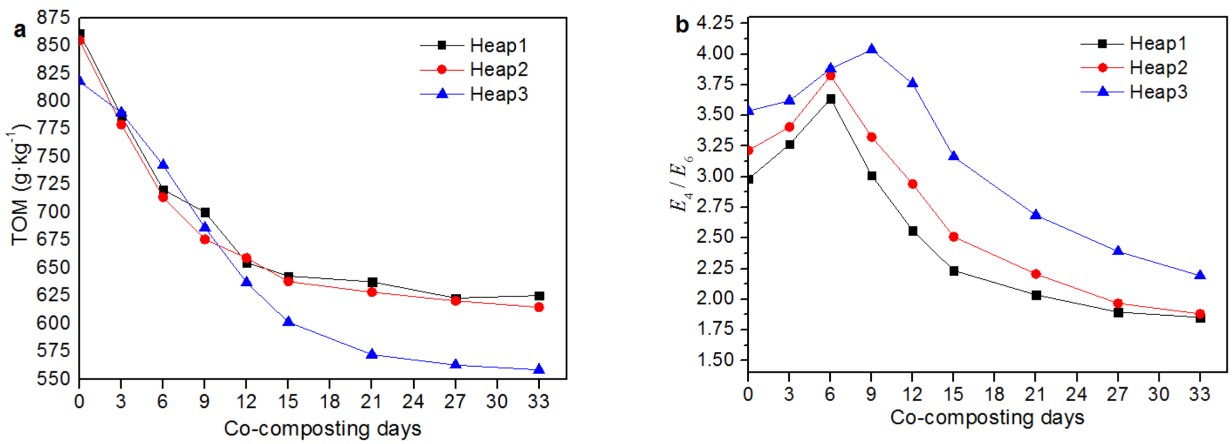

Fig. 3: Dynamic changes in TOM (a) and E4/E6 (b) during co-composting.

for EC, values of 2.16, 2.13 and 1.82 were observed in each heap respectively. At the level of response and stabilization speed, heap 1 and heap 2 showed a better performance than heap 3.

Degradation and resynthesis of organic matter: In the typical composting process, the organic matter (OM) not only goes through the degradation process, but also undergoes the process of resynthesis and polymerization. During the co-composting process of KW-FS-SS, the content of TOM kept declining and finally stabilized for all heaps (Fig. 3a). From the slope of the curve, it can be seen that the degradation of OM occurred mainly in the early and middle stages of co-composting. Except for the slow start in heap 3, there was no significant difference in the decomposition rate of OM for each treatment. After the co-composting process for 33 days, the degradation rates of OM in each heap were 27.39%, 28.05% and 31.69% respectively. The heap 3 had a longer duration of high temperature, more complete degradation of OM, so the degradation rate of heap 3 was the largest, but there may be the risk of excessive degradation. On the other hand, the E_4/E_6, a ratio of absorbance of humic acid at 465 nm and fulvic acid at 665 nm, is often used to characterize the degree of condensation and aromatization of humus in the compost maturity evaluation (Wong et al. 2011). In general, with the co-composting proceeding, small molecules of organic acids continue to synthesize macromolecular substances with high condensation degree, resulting in a reduction in the E_4/E_6 ratio. As shown in Fig. 3b, a trend of increase first and then decrease was observed in all the heaps during the co-composting process of KW-FS-SS. In the early stages, the decomposition of the organic substance produced a large amount of small organic acids with the increasing temperature and the improving of microbial activities, which led to the increase of the E_4/E_6. Afterwards, a decrease of E_4/E_6 in each heap was observed, which showed a strong action of humic condensation and aromatization. At the end of the co-composting process, the E_4/E_6 of each heap decreased to 1.885, 1.908 and 2.214, respectively. Therefore, heap 1 and heap 2 had a faster response and a better maturity than heap 3.

Transformation and loss of nitrogen: The nitrogen loss in the co-composting process determines the fertilizer efficiency of the final product, and the release of nitric gas can cause the unpleasant odour and environmental pollution. Studying the law of transformation and loss of nitrogen is helpful to optimize the strategy of co-composting of KW-FS-SS in the islands. The changes of TN, NH_4^+-N and NO_3^--N with the time of co-composting are shown in Fig. 4.

From Fig. 4a, it was found that TN increased first and then decreased, but the change of TN content was not significant before and after composting, which was consistent with the results by Chazirakis et al. (2011) in the co-composting experiments on sewage sludge, municipal solid waste and yard waste. After aerobic process, a large number of nitric wastes were decomposed into N_xO_y, NH_3, N_2 and released from the reactor. Thus, in theory, the content of TN should obviously reduce. However, with the severe degradation of OM during the co-composting process, a substantial reduction in heap mass occurred because of the loss of carbon, nitrogen and the evaporation of water. The actual decrease of TN was masked by the concentration effect, which made TN perform a slight change. At the first 6 days, all heaps showed a rapid increase in NH_4^+-N (Fig. 4b), which indicated that the ammoniated bacteria could propagate rapidly at the early stages of co-composting process, thus, the organic nitrogen in the substrate was sharply broken down and released a large amount of NH_4^+-N. In the biological nitrification system, the nitrifying bacteria are extremely sensitive to temperature changes, and only below 35°C they can carry out the normal physiological metabolic activities

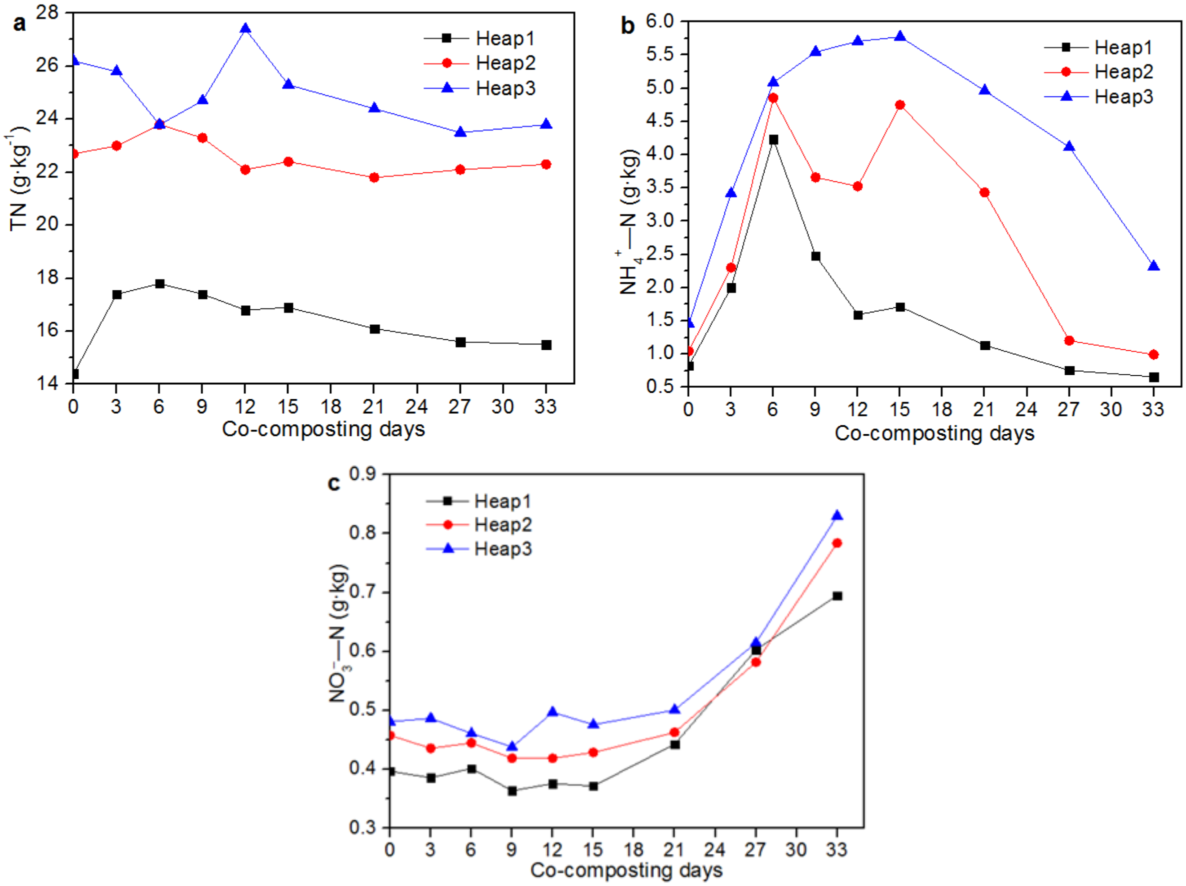

Fig. 4: Dynamic changes in nitrogen forms during co-composting.

(Meunchang et al. 2005). As shown in Fig. 4c, no significant change of NO_3^--N was observed before 15 days. During the prophase and metaphase of the co-composting process, the activity of nitrifying bacteria was seriously inhibited due to the high temperature inside the heaps, resulting in a slow speed of proliferation and a weak nitrification. Hence, the NH_4^+-N could not be converted into NO_3^--N in time, which led to the accumulation of NH_4^+-N and the loss of nitrogen mainly in the form of NH_3. In the late stages of co-composting, an obvious decrease in NH_4^+-N and increase in NO_3^--N were observed in all the heaps.

Dynamic changes in biological toxicity: GI is the most sensitive indicator of compost maturity by monitoring the germination rate of seed and the elongation of root, which can reflect the development trend of compost toxicity and predict the degree of composting process (Zucconi et al. 1981, Zhang & Sun 2014). In the co-composting process of KW-FS-SS, the GI in all the heaps showed a decline for a short-term and then continued to rise, eventually became stable (Fig. 5). In the first 3 days of heap 1 and heap 2, as well as the first 6 days of heap 3, a slight decrease in GI was observed in the three heaps due to the release of high concentration of ammonia and organic acids, such as phenolic acids and volatile fatty acids, which strongly inhibited seed germination and early seeding growth (Zhang & Sun 2014, Awasthi et al. 2015). As the co-composting process progressed, in all heaps, the GI value increased until the end of the composting cycle, indicating that the original material gradually transformed into the simple inorganic and stable humic. Hence, all kinds of wastes became more and more stable with reduced phytotoxicity. After the co-composting process, the GI value of each treatment exceeded 100% and finally reached 137.9%, 125.8% and 141.6% respectively. This indicated that the products produced beneficial nutrients to promote seed germination and root elongation instead of inhibiting its activity. The GI of 80% has been used as a minimum limit to indicate a phytotoxic-free compost product (Wei et al. 2000, Han & He 2015). The heap 1 and heap 2 achieved full maturity first on the 12th day, and for heap 3, it was on the 21st day, which indicated that heap 1 and heap 2 spent shorter time to reach the standard of harmlessness and stability than heap 3.

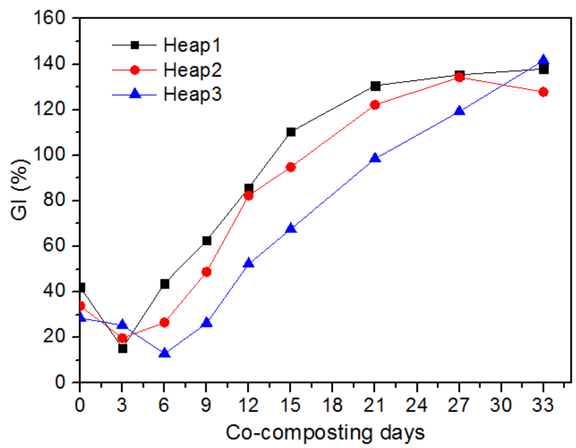

Fig. 5: Dynamic changes of GI during co-composting.

CONCLUSION

1. The results indicated that applying the aerobic composting technology to the solid waste treatment in the mixed system of kitchen waste, faeces and sewage sludge with co-amendment of sawdust and cornstalk was feasible.
2. Through the monitoring of co-composting process for 33 days, it was found that there was a good dynamic correspondence among the indicators. Moreover, through the longitudinal comparisons of the three co-composting processes, it was visibly clear that a more rapid start-up and a much shorter period of time for compost to become stable occurred in heap 1 and heap 2, which can be attributed to the better initial condition.
3. On analysis of technique and economics, the optimal mixed ratio was 4:1 (TMW:TMA), which was suitable to the practical condition with a better efficiency for waste treatment and a low cost of amendment in the island. However, further studies on the harmless effect and fertilizer efficiency of the co-composting products are needed to provide technical support for the improvement of coral sand soil.

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