Research Paper

In-vessel co-composting – a rapid resource recovery option for septage treatment in Indian cities

Anu Rachel Thomas, Martin Kranert and Ligy Philip

ABSTRACT

Septage management is a challenging task across India as more than 44% of the population depends on septic tanks for human waste management. Septage collected from Chennai city, India, was found to be rich in nutrients even though the total solids content (<2%) and C/N are low. The current practice of septage disposal in Chennai city is co-treatment in existing sewage treatment plants. The main drawback of this method is that treatment efficiency could deteriorate if the organic load increased much beyond the design load of the treatment plant and would result in poor treated-water quality. In this context, the present study focused on the potential of in-vessel co-composting as a sustainable treatment option. In order to enhance the co-composting process, suitable co-substrates were identified for making the process efficient and cost-effective. The area under the temperature profile during composting was used as an assessment tool for the identification of the proper mix. Addition of mixed organic waste and coir pith waste (bulking agent) to the dewatered septage gave the highest area among the different combinations. Different waste combinations were investigated in order to assess the suitability for field scale application.

Key words | co-substrates, end use, fertilizer, in-vessel co-composting, maturity test, septage

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INTRODUCTION

Around the globe, about 2.7 billion people, i.e. 40% of the entire world's population are served by onsite sanitation technologies (Strande 2014). In low and middle income countries, there is typically no management system available for the faecal sludge. At present, around 44% of the total population in India depends on septic tanks for their sanitation (Census 2011). Septage comprises the sludge and liquid that are present in septic tanks and are not transported through sewers. The annual septage generation in India is estimated as 0.12 million tonnes per day (Census 2011; Radford & Sugden 2014). Methods such as sludge drying, reed beds, anaerobic digestion and co-treatment were explored for septage treatment. Only a few studies focus on the possibility of recovering the nutrients from septage and converting it into a useful resource. Cofie *et al.* (2009) investigated co-composting as a practical solution in Ghana for faecal sludge treatment in which septage was treated with organic solid wastes in windrow piles. Sharholy & Ahmad (2008) reported that 42% of the average composition of municipal solid waste generated from Indian cities comprised of compostable organics or mixed organic waste (MW) which include fruits, vegetables and food wastes. However, the majority of the organic wastes end up in landfills without proper attention. Hence, there is a pressing need for an integrated solid waste management practice.

Numerous studies have been conducted to treat organic waste through in-vessel composting. The main

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advantages of such systems are less footprint and odour generation. In addition, a controlled condition can be achieved which further results in better compost quality at a much faster rate. Additionally in-vessel composting has fewer hygiene issues when compared to windrow composting. Since septage contains many pathogens (Yen-Phi *et al.* 2010), hygiene is of great concern. Even though co-composting can be an effective method for septage treatment, the identification of suitable co-substrates from a nearby location is essential in order to enhance the efficiency of co-composting process. Springer & Heldt (2016) reported that ten different locally available bulking agents (BAs) in Tamil Nadu have the potential for sludge composting. However, the effectiveness of those BAs for septage composting was not studied. Among the 11 BAs mentioned, coir pith, sugarcane bagasse and wheat straw reported to have relatively high water-holding capacity and air-filled porosity irrespective of lower carbon to nitrogen (C/N) ratios. Septage has a low C/N ratio, high moisture content, poor structure and free air space (FAS) and so cannot be composted alone. The addition of different waste streams can improve the structure and can create favourable conditions for aerobic composting (Meng *et al.* 2017). Even though the BAs available in Tamil Nadu were characterized based on physical properties by Springer & Heldt (2016), to select the appropriate one for septage co-composting, a better assessment tool is essential. Külcü & Yaldiz (2014) reported the usefulness of estimating the area lying under the compost process temperature profile as an assessment tool for thermophilic composting since it directly correlated to organic matter degradation. However, no studies have been conducted so far to determine the appropriate co-substrates for septage co-composting. Moreover, ensuring the hygienization of septage for further usage is seldom studied.

The present study focused on identifying suitable co-substrates for effective septage co-composting using the area lying under the compost process temperature profile as the assessment tool. Three trials incorporating different waste combinations were carried out to understand the compost dynamics and compost quality. Efforts were also made to confirm the final compost applicability as plant fertilizer using maturity tests.

MATERIALS AND METHODS

The septage was collected from Zone IV of Chennai city, Tamil Nadu, India, which covers the southern part of the city. The wastewater generated in Zone IV of Chennai city is conveyed to the treatment plant at Nesapakkam. The Nesapakkam sewage treatment plant (STP), Chennai city is operated 24 hours per day with a total capacity of 117 MLD. The location map showing the different points of sample collection and the Nesapakkam sewage treatment plant is given in the supplementary material (Figure S1, available with the online version of this paper). One hundred and twenty samples per season for analysis were collected during summer and winter season. The number of samples collected during the two seasons of sampling was determined statistically and was explained in detail in an earlier paper (Krithika *et al.* 2017). The septage samples for characterization were collected during discharge of the pumper truck after the material has been mixed. In the present study, three samples were collected from each truck at the beginning, middle and end of the discharge of septage to the collection well of Nesapakkam STP to get a fairly representative sample. The methodology of sampling is comparable to earlier studies which show the seasonal variation of septage in Ain Ghazal, Jordan (Halalsheh 2008). The samples were analysed for various parameters like solid content, organics and nutrients. The detailed procedure for the analysis was described previously in Krithika *et al.* (2017).

Septage was dewatered using a laboratory-scale sand drying bed. The dewatering setup consisted of a 100 L capacity overhead septage storage tank, inlet pipes, drying bed, under drainage pipe (1% slope) and a filtrate collection tank. The dewatering procedure was adapted from Cofie *et al.* (2009). The MW used for septage co-composting mainly comprised of green vegetables (uncooked) and food waste (cooked waste) obtained from the hostel mess at the Indian Institute of Technology Madras campus, Chennai, India. Cow dung, soft wood, straw, coir pith and bagasse were procured from the neighbourhood of Indian Institute of Technology Madras campus, Chennai, India. The maximum particle size of the feed stock materials was restricted to 2–4 cm. The composting experiments were carried out in vertical drums having a diameter of 350 mm and height of 800 mm with a volume of 75 L. The effective volume of the system was 50 L. The entire setup was insulated using glass wool and the compost matrix was supported with a perforated mesh. The leachate generated was quantified using a graduated cylinder. Air was supplied using an air blower at an aeration rate of 0.48 L/kg dry matter.min (Jiang *et al.* 2011). Two temperature probes (Engineering Gallery, India) were inserted (one at 10 cm below compost surface and one at 10 cm above the porous mesh) in each compost matrix. The temperature data thus obtained were stored using a data logger. The study was conducted in two phases: the first phase focused on the identification of suitable co-substrates where temperature was the only key parameter monitored and the second phase involved the optimization of feedstock composition. Hence, compost sampling was done once in 2 days and analysed for various parameters: pH, electrical conductivity (EC), temperature, water content, organic matter loss, nitrogen loss, change in FAS, ammoniacal-nitrogen (NH_4^+-N), nitrate-nitrogen (NO_3^--N), total phosphorus (TP) and potassium (K) and C/N ratio. A seed germination assay was used to determine the final compost quality. The detailed compost sampling and analytical procedures for each parameter (Standard Methods for the Examination of Water and Wastewater 2012) during composting are given in the supplementary information (Section 1, available online).

RESULTS AND DISCUSSION

Chennai septage sample characteristics and pre-treatment

Septage samples collected from the septage collection facility at Nesapakkam STP, Chennai city were characterized in order to understand the nature of septage prevailing in the city. The detailed characterization of septage used for the present study is given in Table S1 (available with the online version of this paper). The results revealed the highly variable nature of septage. The variability is not only seasonal and regional, but also due to other factors, including number of households, cleaning frequency, pumping rate and vacuum suction ratio (Krithika *et al.* 2017). The results showed that the maximum total solids concentration of 17,467 mg/L, chemical oxygen demand of 6,656 mg/L and ammonia-nitrogen (NH_4^+-N) of 129 mg/L resembles a low strength faecal sludge as reported by Heinss *et al.* (1998). The water content was much higher than the solids, which necessitated solid–liquid separation (dewatering) before treatment. Hence, septage was pretreated using the sand drying bed (Cofie *et al.* 2009). The prime purpose of dewatering was to increase the solid content of septage and for the ease of handling large volume of wastewater prior to composting. In the present study, the septage contained $\geq$98% water. The raw septage and the filtrate quality obtained from sand drying bed after one cycle is given in Table S2 (available online). More than 80% of the volume was reduced by percolation in drying beds and the rest by evaporation. The filtrate from the bed still contained nutrients and organics which can be treated in waste stabilization ponds or constructed wetlands before discharge (Ramprasad & Philip 2018). After 4 days, at the end of the dewatering cycles, the septage contained 30–35% total solids and 65–70% moisture content and was finally removed from the bed surface manually. The C/N ratio of the septage solid was found to be 8.8 which is lower than the desired value for proper and effective composting. Hence, it was essential to add co-substrates to attain an optimum C/N ratio for composting (Springer & Heldt 2016).

Determination of suitable co-substrates for the effective in-vessel co-composting of septage

Although septage contains nutrients and organics, the composting of septage alone is not feasible due to its deprived structure and small particle size that cause poor gas permeability. Cofie *et al.* (2009) explored the feasibility of using organic wastes from households and markets as co-substrates for windrow composting of faecal sludge. Although the study emphasized the effect of mixing ratio and turning frequency for composting, information regarding the appropriate BA was missing. Also the probable generation of a large quantity of leachate during composting of wastes with high water content, like faecal sludge and organic waste, was not addressed properly.

The common practice of adding BA during composting is to reduce the moisture content and to provide sufficient air filled porosity (Eftoda & McCartney 2004). Therefore, the major criteria for choosing the BA include water-holding capacity, FAS and mechanical strength for successful compost operation. The study conducted by Springer & Heldt (2016) explored the potential of 11 locally available materials to be used as effective BAs for sludge treatment based on analysis of the physical properties. From among them, three BAs were chosen for the present study, namely straw (BA1), coir pith (BA2) and bagasse (BA3). The selection was made based on the water-holding capacity, air filled porosity, mechanical strength, and cost and availability of the materials in the study area. The physical characteristics of the chosen BAs are given in Table S3 (available online).

The addition of co-substrates could improve the composting conditions by providing high porosity, C/N ratio and enough moisture content. Moreover, the addition of organic waste can even enrich the final compost. Hence, co-composting may be able to treat two or more different types of waste at the same time. Kalamdhad *et al.* (2008) reported the application of mixed vegetable matter in rotary drum composting resulted in the production of good quality compost at a much faster rate. However, the use of MW as co-substrate for septage co-composting is seldom practised. Meng *et al.* (2017) suggested that the results of the combined addition of spent mushroom substrate and wheat straw (suitable BA) was more favourable than the addition of spent mushroom substrate or wheat straw alone during sewage sludge composting. According to Külcü & Yaldiz (2014), the evaluation of the area lying under the temperature profile can be used as an assessment tool for evaluating the effectiveness of composting rather than relying only on physical properties of co-substrates.

The experimental setup of in-vessel co-composting system and the temperature profile during composting of different mixtures (trials) are given in Figure 1(a) and 1(b). The area lying under the temperature profile of different trials during composting is illustrated in Table S4 (available online). From the temperature profiles, it is evident that septage with BA alone would not achieve the thermophilic phase of composting. The temperature rise is attributed to the metabolic heat generated during microbial activity. The lack of readily available organic matter in the mixture resulted in less heat production thereby resulting in a lower temperature development during composting. However, a slight increase in the temperature from the ambient temperature was observed in all the mixtures. A mixture of coir pith with septage showed slightly higher temperature profile and largest area under the curve than that of straw and bagasse. This may be due to the thermal insulating property of coir pith. As the dissipation of heat generated during the self-heating process was slower, there was rise in the temperature within the bulk of the coir pith and septage mixture. MW was chosen as one of the co-substrates other than BA for the study as it showed potential degradation with retention of higher temperature using rotary drum composting (Kalamdhad *et al.* 2008). The temperature profile of the different compost mixtures containing MW clearly showed

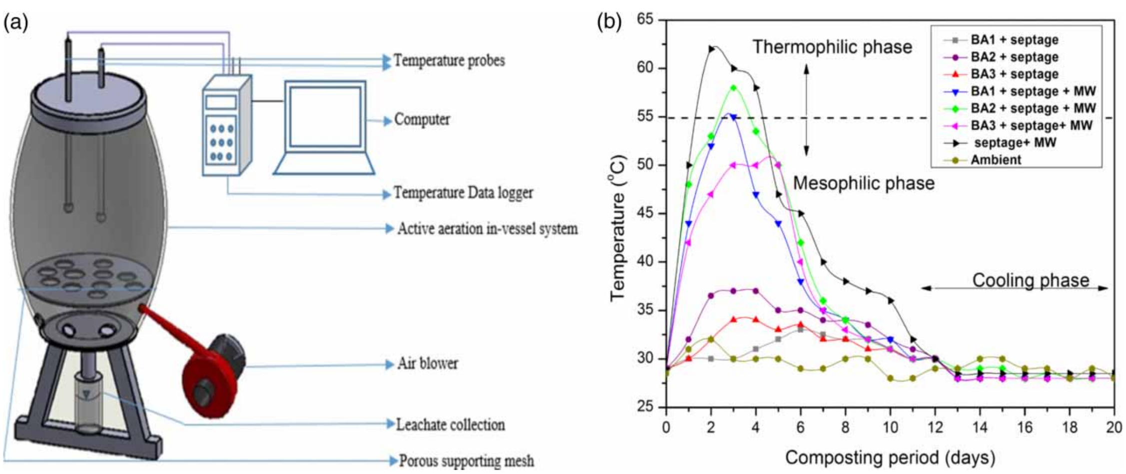

Figure 1 | (a) Experimental set-up of in-vessel co-composting system; (b) temperature profiles of trials with combination of various BAs, septage and MW. BA1: straw; BA2: coir pith; BA3: bagasse.

the attainment of a thermophilic phase during composting. Retention of high temperature (>55 °C), for more than 3 days, enhanced the pathogen inactivation in septage as per USEPA (2003). The addition of MW to the BA and septage mixture increased the temperature of the compost mix significantly. This was mainly due to the availability of readily degradable organics contributed from MW (Meng *et al.* 2017). As shown by the temperature, profile, the mixture of septage and MW achieved a maximum temperature of 63 °C, which was higher than the other mixtures. Moreover, the area under the temperature curve was maximal for the mixture of septage and MW. The higher temperature might be due to the release of an immense quantity of metabolic heat, resulting from the microbial decomposition of MW. The retention of higher temperature over 3 days was observed for this mixture.

These results indicated that MW to be an appropriate complementary material for septage composting. However, this mixture having a high initial water content, can lead to generation of a large quantity of leachate during thermophilic composting (Varma & Kalamdhad 2014). Hence, the addition of BA with septage and MW is necessary to reduce the leachate production. From Figure 1(b), the mixture of coir pith, septage and MW found to have highest area under the temperature profile among the combinations. Coir pith is used as a BA in the current study as it is has high water-holding capacity (12.3 g water/g dry substrate) and porosity (Springer & Heldt 2016). The high lignin (35–54%) and cellulose (23–43%) contents of the coir pith contribute to its physical stability which does not change markedly with moisture content. Also coir resists bacterial or chemical decomposition and breakdown due to high protective lignin content. Its ion exchange/adsorption properties can be utilized to adsorb important plant nutrient, e.g. N in its NH_4^+ and/or NH_3 form, protecting it from losses such as during composting of N-rich wastes (Okon *et al.* 2012). Therefore, it is appropriate to use coir pith as the BA rather than straw and bagasse.

Compost dynamics during in-vessel co-composting of septage for different waste combinations

The proper feedstock composition plays a crucial role in the success of composting. In-vessel co-composting studies were carried out to obtain the appropriate mixing combinations of co-substrates identified in the previous experiments. The quantity of waste ingredients and the characteristics of initial compost mix are given in Table S5 (available online). Wood chips were added to resist compaction during composting and to help maintain air-filled pores throughout the compost matrix (Haug 1993). Adegunloye *et al.* (2007) suggested that the addition of cow dung serves as a booster and can help in faster degradation of organic wastes. The temperature profile during in-vessel co-composting is given in Figure 2(a). All trials showed a sudden rise in the temperature directly after the start of composting, which indicated the presence of high concentrations of readily available biodegradable carbon in the compost matrix. Further increases in temperature lead to the thermophilic phase. Temperature development to an optimum range of 50–60 °C ensures effective composting (Wong *et al.* 2011). Among the trials, trial 3 showed higher temperatures during composting due to the higher heat retention capacity of coir pith as in this trial, 33.3% of feedstock was occupied by coir pith. The final compost temperature was reduced to ambient temperature indicating the stability of the compost matrix (Haug 1993).

Figure 2(b) displays the pH values during co-composting. The pH value at the start of composting was 4.1, 5.0 and 5.9, which then gradually increased to 8.0, 7.5 and 8.0 in trial 1, 2 and 3, respectively. The maximum increase in pH, in all trials, occurred during thermophilic phase. This may be due to the solubilization of ammonia released during protein degradation to form ammonium ions (Sánchez-Monedero *et al.* 2001). In trial 1, further decrease in pH was observed during nitrification, while in trial 2 and 3, there was no significant change in pH at the end of composting. This may be due to the net buffering effect of coir pith in the systems (Kithome *et al.* 1999). The final compost of all trials had a pH in the range of 7.1–8.6 which indicates a stable compost.

The change in EC during in-vessel septage co-composting is shown in Figure 2(c). The initial decrease in EC might be due to the release of mineral salts and ammonium ions through the decomposition of organic material (Varma & Kalamdhad 2014). The EC values showed a decline at the final phase of the composting. This may be due to the volatilization of ammonia and the precipitation of

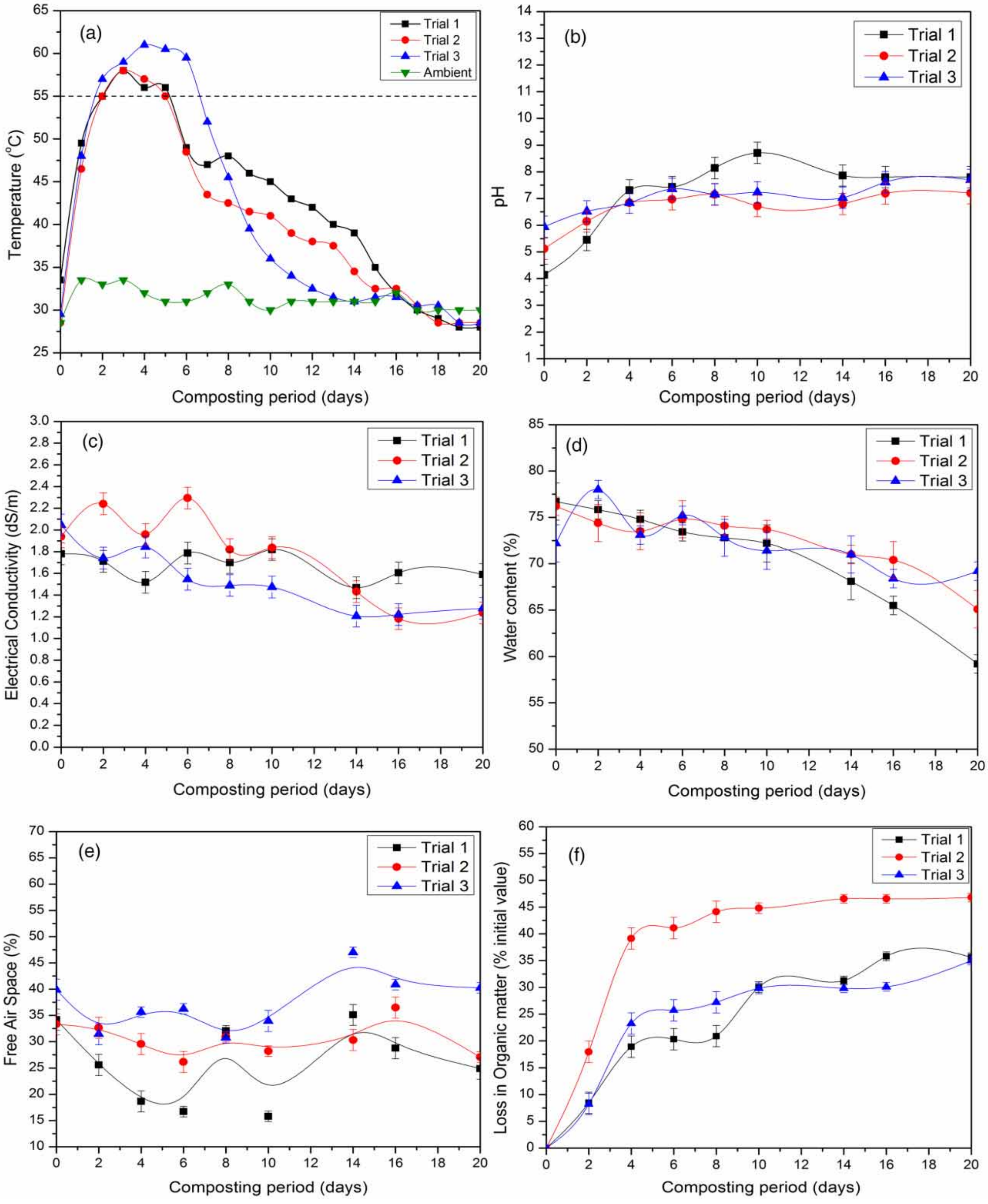

Figure 2 | Change in composting parameters: (a) temperature profile; (b) pH; (c) EC; (d) water content; (e) FAS; (f) loss of organic matter; (g) loss in total nitrogen; (h) ammonia-nitrogen; (i) nitrate-nitrogen; (j) total phosphorus; (k) potassium; (l) C/N ratio. (*Continued*.)

mineral salts. Since the final compost in all trials had an EC value $\leq$4 dS/m, it is not toxic for plant growth.

Moisture loss in the composting process occurs because of vaporization due to heat produced during organic matter degradation. Figure 2(d) shows the reduction in moisture content during composting. Since the moisture loss and leachate production have a direct correlation, in this study leachate production was quantified and is presented in

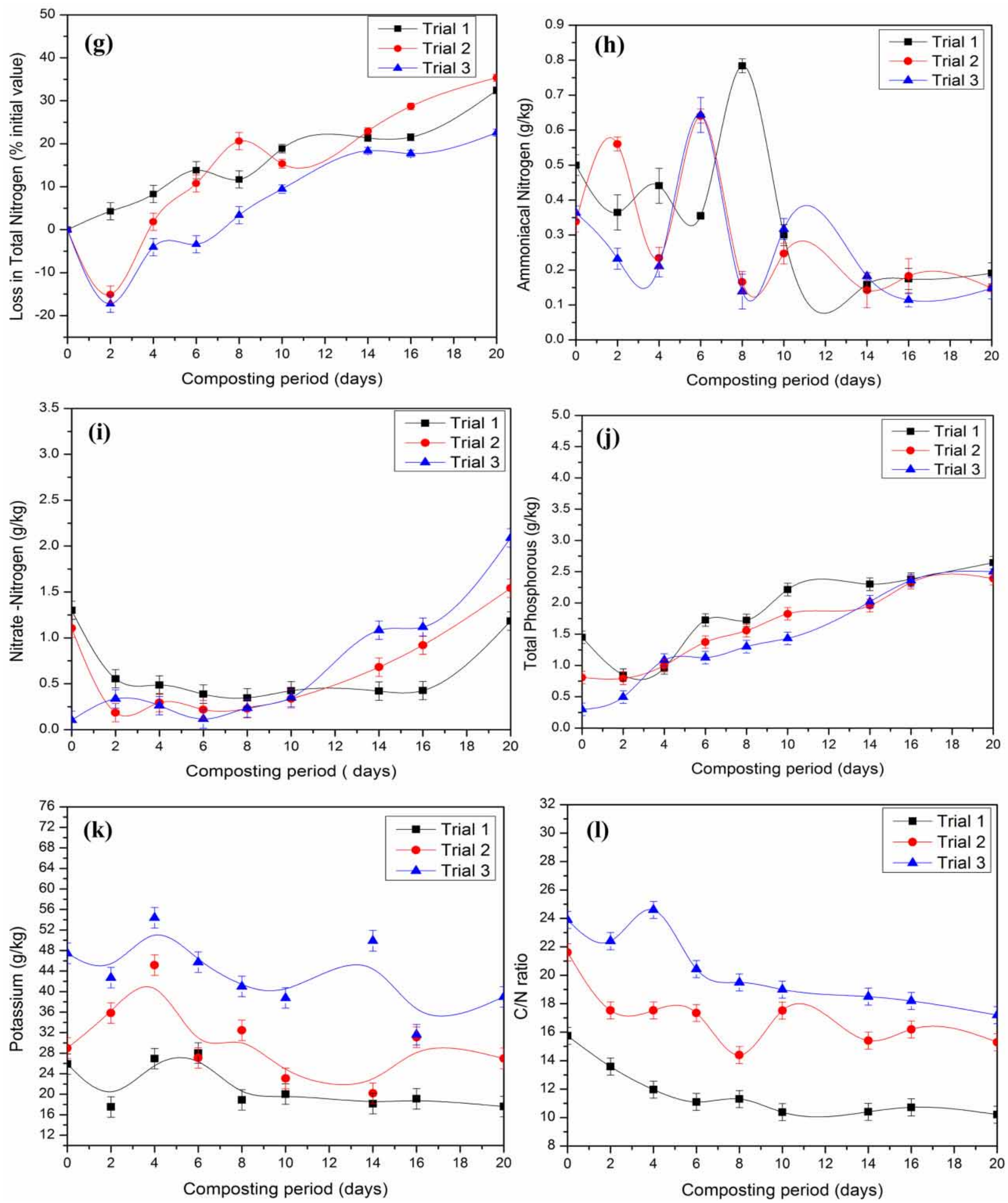

Figure 2 | Continued.

Figure S2 (available online). The moisture content (wet basis) at the start of composting was found to be 78%, 74% and 68% in trials 1, 2 and 3, respectively, which are more than the preferred moisture range (55–65%). During the decomposition of organic waste (vegetable waste having 92.6% moisture content), bound water will be released. The excess initial moisture and bound water contributed to the increase in leachate quantity during the initial stages of composting especially in trials 1 and 2. At the earlier stage of composting, more organic matter

(% volatile solids) degradation occurred and the water vapour thus produced was trapped by the BA (coir pith) which resulted in the higher moisture content of compost samples from trial 2 and 3. A similar trend was reported by Varma & Kalamdhad (2014) during drum composting of vegetable waste, saw dust, cow dung and dry leaves. FAS is a direct measure of oxygen availability in the system which shows the prevalence of aerobic condition. Due to moisture loss, porosity in the composting pile reduced significantly and the change in FAS during composting is given in Figure 2(e). Since FAS depends on wet bulk density and porosity, the decrease in porosity and increase in wet bulk density resulted in the decrease in FAS. The FAS was maintained above 30% (oxygen supply >5%) in trial 1 and 3 and below 30% in trial 2 during the course of composting. This can be attributed to the increased organic matter loss thereby yielding significant mass reduction.

The majority of the loss in organic matter and total nitrogen occurred during the initial stages of composting in all trials, especially during the thermophilic stage of composting. The loss in organic matter and total nitrogen during composting is depicted in Figure 2(f) and 2(g), respectively. The major available nutrients for plants include nitrogen (especially in the form of ammonia-nitrogen and nitrate-nitrogen), potassium and phosphorus. The change in ammoniacal-nitrogen, nitrate-nitrogen, potassium and phosphorus are given in Figure 2(h)–2(k). Composting results in the increase in phosphorus and nitrate content while potassium level was found to be stable. Ammonia content was high initially and decreased subsequently. The final nutrient content was determined by adding all the content in a dry weight basis. In this study, the nutrient value of trial 1, 2 and 3 were 4.1%, 4.7% and 5.7% dry weight, respectively which was ≥4% dry weight (HKORC 2005). Hence, the final product can be considered as good quality compost for application as fertilizer.

Compost maturity and quality

The change in C/N ratio indicates the degree of organic matter degradation and stabilization of final ripened compost (Varma & Kalamdhad 2014). Figure 2(l) shows the variation of C/N ratio with time. The initial compost mixture had a C/N ratio of 15, 20 and 24 in trial 1, 2 and 3, respectively. The optimal range for composting is 15–30 (Haug 1993). The low C/N ratio was selected for initial feedstock in order to reduce the bulking material requirement and to treat more septage solids. The C/N ratio showed a decreasing pattern in all trials. The C/N ratio of final compost obtained was 10.2, 15.3 and 17.2 for trial 1, 2 and 3 respectively. Wong *et al.* (2011) described the seed germination index as a direct bio-indicator for compost maturity (maturity test) which indicates the phytotoxic effects of the final compost. The results of the germination test are given in Table S6 (available online). The criterion for phytotoxicity-free compost is germination index ≥80%. The germination index was 149%, 137% and 118%, respectively, for trial 1, 2 and 3. Hence, in this study, the in-vessel system produced highly stable and phytotoxicity-free compost within 20 days of composting. The properties of the final composting products from all treatments are presented in Table 1. The nutrient contents of compost products obtained in all trials satisfied the requirement to use them as organic fertilizers as per the HKORC (2005) criteria.

In the present study, in-vessel co-composting was evaluated as a decentralized treatment option for septage management in Indian cities. Co-composting seems to be a less expensive and sustainable treatment option compared to other available treatments currently practised in India as it treats not only dewatered septage but also MW. Hence, the overall cost will be lower for co-composting compared to the available treatments, such as co-treatment with sewage or anaerobic digestion. It can be even carried out using a home-composter. The cost of an ordinary aerobic

Table 1 | Properties of the final compost products from in-vessel septage co-composting at trial 1, 2 and 3

Parameters	Standard values[a]	Trial 1	Trial 2	Trial 3
Ammoniacal-N (mg/kg dw)	≤700	190.4 ± 4.8	148.4 ± 5.3	147.8 ± 5.3
C/N ratio	≤25	10.2 ± 0.5	15.3 ± 0.2	17.2 ± 0.8
pH value	5.5–8.5	7.8 ± 0.10	7.2 ± 0.02	7.7 ± 0.02
Seed germination index (%)	≥80	149	137	118
Total N, P, K	≥4% dw	4.1 ± 0.5	4.74	5.7 ± 0.5

[a]Compost and soil conditioner quality standards for general agricultural use (HKORC 2005).

home-composter used in the present study was Rs 2,400 (US$34.3)/unit with a capacity of 50 L. The price details of all components associated with an in-vessel composter are given in Table S7 (available online). The total energy consumption for the entire composting operation of 30 kg of raw waste is 9.7 kWh and the cost associated with the operation is Rs 1.94 (~3 US cents) per kg waste treated. The cost of processed compost/kg is around Rs 25/- (0.36 US$).

CONCLUSIONS

In-vessel co-composting was investigated as a potential resource recovery option for septage treatment in Indian households. The co-substrates suitable for effective septage co-composting were identified. The compost dynamics of different waste combinations (produced by changing the quantities of dewatered septage, co-substrate and BA) were investigated for field-scale application. The combined addition of MW (as main co-substrate) and coir pith waste (as BA) found to be appropriate for septage composting as it significantly improved the composting conditions. The study also revealed that the composting process was efficient even with a smaller amount of coir pith. The addition of coir pith to less than 16% of the total volume of compost mixture is sufficient for field application. The in-vessel co-composting of septage could be easily adapted mainly in urban Indian households and communities due to the lower footprint requirement and rapid production of hygienic and good quality compost.

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