RECENT ADVANCEMENTS IN CHEMICAL, ENVIRONMENTAL AND ENERGY ENGINEERING

Bio-reserves inventory—improving substrate management for anaerobic waste treatment in a fast-growing Indian urban city, Chennai

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Abstract

India is one among the Asia's newly industrialized countries, in which urban centres generate large amount of municipal solid wastes due to the rapid urbanization. To demonstrate urban waste potentials for biogas production by anaerobic digestion, a comprehensive analysis on the availability of organic waste hotspots and its biogas potential for the exemplary case of Chennai, India, was undertaken. The identified hotspots and their biogas potential were plotted with Geographical Information System as thematic maps. The results of biogas potential tests revealed strong variations in the biogas potentials of individual waste streams from 240.2 to 514.2 mL_N/g oDM (organic dry matter) with oDM reduction in the range of 36.4–61.5 wt.-%. Major waste generation hotspots were identified from the surveyed urban bio-reserves and the biogas potentials within an effective area of 5 km radius surrounding the hotspot were estimated. It was found that the biogas potential of individual hotspots ranged between 38.0–5938.7 m^3/day. Further results revealed that the biogas potential during anaerobic co-digestion, by considering nearby bio-reserves in the effective areas of major hotspots, with and without residential organic waste, ranged between 4110.4–18–106.1 m^3/day and 253.2–5969.5 m^3/day, originating from 144.0–620.0 tons and 3.1–170.5 tons, respectively. Despite variations in the composition of the wastes, the Carbon/Nitrogen ratio, oDM reduction, biogas production and substrate availability were improved during co-digestion of nearby bio-reserves within the major hotspots, thereby improving the prevailing barriers in substrate management during anaerobic digestion of wastes.

Introduction

Global population currently reached 7.5 billion with the second highest being shared by India with a population of about 1.3 billion (World population review data 2019). In concurrence with the increasing population, the solid waste generation is rising worldwide of about 2.01 billion tons (The world bank data 2019). Of this, a minimum of 33% of waste generated is not treated in a proper manner. It has been forecasted that the solid waste generation is estimated to increase by 70% during 2050; hence, there is an urgent need to focus on effective waste management, treatment and disposal options (The world bank data 2019). Among various countries, India is expected to be the most populous country among the world by 2030, which will lead to further increase in the waste generation quantities (World population review data 2019). In addition to the increasing population, there are other issues that increase the solid waste generation in India that mainly includes urbanization, lifestyle changes, economic growth, lack of employment opportunities in rural India, sectoral income changes etc. (Karthikeyan et al. 2018; Bhat et al. 2017; Ahluwalia 2016; Chaudhuri 2015; Vij 2012). Also, India is one among the Newly Industrialized countries (NIC) in Asia (Population Reference Bureau (PRB) 2016; Speier et al. 2018; Fromhold 2001). With growing industrialization including infrastructure and service sectors in Indian urban cities, there is a further

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increase in the urbanization rates, which subsequently increases the municipal solid waste (MSW) generation per person (Neelmani and Sudeshna 2014; Kumar et al. 2017). Hence, Solid Waste Management (SWM) is a major problem for multiple urban local bodies in India that needs to be addressed for efficient treatment and disposal.

The MSW predominantly comprises of organic matter varying from 40.2 to 51.0 wt.-% (Mondal et al. 2016; Dhar et al. 2016; Speier et al. 2018). Out of the collected MSW in India, only 12 wt.-% is processed and treated, while the rest is disposed in open dumpsites (Joshi and Ahmed 2016). Improper segregation of the MSW is another setback in SWM, which not only pollutes the environment but also prevents efficient use of the waste's potentials (Nandan et al. 2017; Singh et al. 2012). Hence, suitable treatment option for the utilization of the organic waste from urban MSW needs to be identified.

Biological treatment methods (composting and anaerobic digestion) of organic fractions of MSW are widely preferred than thermal treatment methods (such as incineration, pyrolysis etc.) due to high moisture in the organic fractions of MSW (Velmurugan and Ramanujam 2011). Anaerobic Digestion (AD) of organic wastes is a suitable, widely used and promising technology for utilizing the potency of organic wastes (Pagliaccia et al. 2019; Patil and Deshmukh 2015). AD is the process of biological decomposition of organic matter present in the wastes by anaerobic bacteria in the absence of oxygen through a series of processes such as hydrolysis, acidogenesis, acetogenesis and methanogenesis (Mir et al. 2016). AD process gives out an alternative fuel in the form of biogas and also a nutrient-rich fertilizer. Thus, it provides dual benefits in terms of meeting energy demand and waste management (Cuetos et al. 2008; Okuo et al. 2016; Saboor et al. 2017; Kapoor et al. 2019). However, several technological and non-technological barriers such as high capital cost, weak dissemination policies, lack of knowledge on the waste characteristics, lack of consciousness on technology benefits, operation and maintenance issues, lack of skilled manpower etc. have been reported for the dissemination of biogas technology worldwide (Kemausuor et al. 2018; Mittal et al. 2018; Budiman et al. 2018; Yousuf et al. 2016; Akinbomi et al. 2014). With evidence to the reported barriers, India generates about 2.07 billion m^3/year of biogas out of the estimated potential of 29–48 billion m^3/year (Mittal et al. 2018). To reduce the non-technological barriers, support schemes have been promoted by the Indian Government for the implementation of biogas plants, such as waste to energy programs, the national biogas and manure management program and the off-grid biogas power generation program (Ministry of New and Renewable Energy (MNRE) 2015). However, several authors have reported the technological barriers for AD in the form of inhibitors of individual organic fractions of MSW (such as ammonia, volatile fatty acids,

sulphide, long-chain fatty acids etc.), leading to operational problems as presented in Table 1.

Analysing AD of organic waste streams in India, several authors reported the fundamental need for the adequate substrate management (Mittal et al. 2018; Mozhiarasi et al. 2019; Kim et al. 2012; Barchmann et al. 2016). Co-digestion of different wastes offers an improved substrate management by balancing various parameters of different wastes (Mahanty et al. 2014; Verdaguer et al. 2016; Zhang et al. 2014; Song et al. 2019). It enhances the distribution of macro and micronutrients, pH, reduces the toxicity and improves the biodegradability of organic matter (Alvarez et al. 2010). Also, both carbon and nitrogen content of substrates plays a vital role in deciding the stability and process inhibitions of the AD reactor. Carbon is the major source of energy for the microorganisms whereas nitrogen is required for the microbial growth (Alvarez and Riden 2008; Hills 1979). Several authors observed the enhancement of biogas yield, methane share in the biogas and oDM reduction by balancing C/N ratio during co-digestion of substrates (Sosnowski et al. 2003; Hills 1979; Heo et al. 2004).

Geographical Information System (GIS) is a system to capture, store, analyse and display all kinds of geographical data and the resultant data could be transformed and analysed using GIS tools for an efficient decision-making (Kinobe et al. 2015). GIS has been widely used in various applications

Table 1 Substrate and process inhibitions reported during AD of individual organic fractions of MSW

Substrate	Inhibitions observed during AD of wastes	References
Fruit, vegetable wastes	Volatile fatty acid inhibition	Edwiges et al. (2018); Van et al. (2018); Scano et al. (2014); Bouallagui et al. (2005)
Slaughterhouse wastes	Long-chain fatty acids, ammonia inhibition	Ware and Power (2016); Palatsi et al. (2011); Cuetos et al. (2010)
Fish wastes	Long-chain fatty acids, ammonia inhibition	Nges et al. (2012); Gumisiriza et al. (2009); Aspé et al. (2001)
Food wastes, household wastes	Volatile fatty acids, long-chain fatty acid inhibition	Morales-Polo et al. (2018); Lu et al. (2017); Banks et al. (2012)
Flower wastes	Poor degradation due to hardly degradable lignocelluloses	Alkanok et al. (2014); Jadhav et al. (2013); Lu et al. (2008)
Animal manure	Poor degradability of cellulose	Van et al. (2018); Zhang et al. (2017); Hansen et al. (1998)
Chicken wastes	Ammonia inhibition, sulphide inhibition	Zhu et al. (2019); Fuchs et al. (2018); Salminen and Rintala (2002)

such as hotspot analysis, urban planning, transportation planning, environmental impact analysis, land use/land cover applications, natural resource management etc. and the current study utilized it for hotspot mapping of organic waste bio-reserves in Chennai city. Approaches to hotspot mapping have gained wide applications in various fields such as seismology, volcanology, epidemiology etc. and the quantitative data thus obtained uses mapping tools to provide spatial representation of the data for visualization and data interpretation (Alessa et al. 2008). Further, the extent of hotspot mapping has also been employed to address environmental issues such as climate change, solid waste, environmental pollution etc. For instance, Feyissa et al. (2018) carried out a GIS mapping of climate change vulnerability hotspots in Addis Ababa. Lin et al. (2011) carried out the GIS mapping of hotspots of environmental pollutants in soil and found the evidence of heavy metal pollution which was correlated with the presence of industrial plants and irrigation systems in the nearby area. Metson et al. (2018) mapped the phosphorus hotspots in Sydney's organic wastes to provide opportunities for the stakeholders to identify the possible urban phosphorus recycling strategies. Similar quantification and mapping of organic waste locations helps to identify suitable technologies to facilitate recycling/efficient treatment and disposal of wastes. In order to develop an integrated urban substrate management system for urban areas in Asia's NIC, hotspots of organic waste generation, in the following labelled as bio-reserves, were identified and analysed for the exemplary case of one large Indian urban area. For each hotspot, waste generation, physical and chemical characteristics and biogas potentials were determined. The collected data were subsequently plotted with respect to their spatial distribution using GIS. The plots were utilized to extrapolate biogas potentials for co-digestion of the available waste streams as well as substrate availabilities for effective substrate management. The bio-reserves inventory approach of this article aims to improve the biogas plant site selection which will reduce the transportation cost associated with wastes as well as support the process operation of existing AD treatment plants in Asia's NIC.

Materials and methods

Area of investigation

For the development of the bio-reserves inventory, one of the India's highly populated urban cities, Chennai, with over 9.1 million inhabitants, was selected (IOP 2019). The map of the study area is given in Fig. 1. The Municipal Corporation of Chennai is divided into 15 zones and 200 wards, which are considered for investigation. The city's peak energy demand exceeds 2000 MW (in 2018) which shares nearly 13.5% of the

energy demand of the state of Tamil Nadu which increased from 11,397 MW in 2011 to 14,734 MW in 2018 (Ministry of Power and Energy Department (MPED) 2016; Open Government data (OGD) platform, India 2018; Times of India 2018). This city generates approx. 5400 tons of MSW per day with a per capita waste generation of 0.65 kg/person/day (Greater Chennai Corporation portal 2019). Currently, the MSW collected along with organic fractions of MSW is being disposed in landfills, which leads to significant environmental problems and CO_2 emissions on the city's landfills (Jha et al. 2008; Escamilla-Alvarado et al. 2016).

Organic waste bio-reserves

An organic waste bio-reserve is defined as the location of major organic waste generation in a geographical place, e.g. city or country. Within an urban area like Chennai, these are vegetable, fruit, flower, fish markets, institutions/universities, commercial spaces, slaughterhouses, etc. Within this investigation, the following waste streams were investigated individually:

Vegetable market waste (VMW)
Fruit market waste (FRW)
Flower market waste (FLW)
Slaughterhouse wastes (SHW)
Chicken waste (CHW)
Fish market waste (FMW)
Canteen food waste (CFW)
Residential organic waste (ROW)

An initial survey within the area of investigation revealed that major organic waste generation occurs in approx. 33 chicken shops, 3 major fish markets and 3 mixed markets with vegetable market, fruit market and flower market situated next to each other along with 3 slaughterhouses and multiple canteens of commercial establishments or institutions.

Markets of vegetable, flower and fruits were observed to be concentrated in the same areas. The markets considered in the study were conglomerations of numerous small and individual shops. In terms of waste generation, the detailed compositions of VMW, FLW and FRW were investigated for the exemplary cases of the Koyambedu Wholesale Market Complex (KWMC), Thiruvanmiyur market and Saidapet vegetable market. The Koyambedu Wholesale Market Complex, one of the Asia's largest horticulture markets, contributes approx. 4 wt.-% to the generated MSW in Chennai.

Furthermore, three urban SHW hotspots in Chennai generate both cattle SHW and goat rumen contents (GRC). The daily waste generation rate is around 10 tons of SHW or GRC namely split between Perambur (8–9 tons of SHW per day), Villivakkam (0.5 ton of GRC per day) and Saidapet (0.5 ton of GRC per day). Unlike other markets, CHW is

Fig. 1 Map of study area—Chennai city

generated from decentralized and individual abattoir shops in Chennai. The waste generation rates from 33 chicken shops (25 retail shops and 8 wholesale shops) from different areas within Chennai (Fig. 2) were surveyed. It was observed that, on an average, 269 kg/day/shop of wastes were obtained for wholesale shops whereas for retail shops, the average waste generation rate is 72 kg/day/shop.

There are three major FMW hotspots at Saidapet, Chintadripet and Vanagaram in Chennai. The Saidapet fish market alone generates approx. 9–10 tons of FMW per day. This is due to more number of retail shops in Saidapet market compared to the Chintadripet and Vanagaram fish markets, which generate approx. 3–4 tons and 2–3 tons of organic waste per day, respectively.

Food waste alone shares 8.0 wt.-% in the MSW generated in Chennai (Greater Chennai Corporation portal 2018). There are 195 subsidized canteens all over Chennai run by the Government of Tamil Nadu (Greater Chennai Corporation portal 2018). In order to estimate the food waste characteristics and biogas potential, canteen waste from Central Leather Research Institute (CLRI) campus was investigated for a month. It was found that, average of about 45 kg/day of food waste were generated and the same has been collected and mixed thoroughly, after which the characterization and BMP measurement were carried out. The data on per capita residential organic waste (ROW) generation was retrieved from literature and taken as 40.25% (corresponds to 0.26 kg organic waste/capita/day) of the waste generation rate of 0.65 kg/

Fig. 2 GIS mapping of bio-reserves in Chennai city
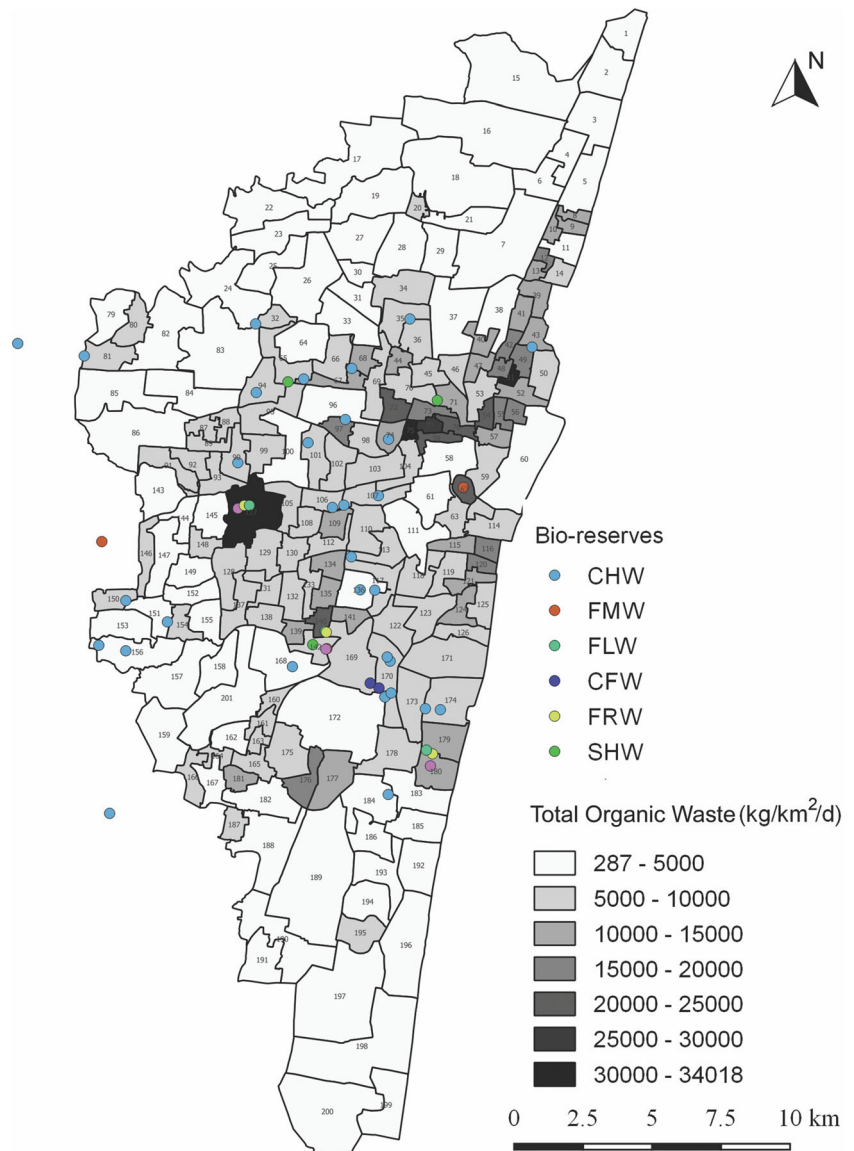
capita/day (Greater Chennai Corporation portal 2018) as compared to the reported value of 41.8% (Nandan et al. 2017). The per capita organic waste generation lies with the reported range for developing countries as 0.14–0.32 kg/capita/day (Philippe and Culot 2009; Bolaane and Ali 2004; Adama 2007; Parizeau et al. 2006). Hence, the household organic waste generation was taken as 0.26 kg/capita/day and the biogas potential was projected for different wards of Chennai city.

Waste sampling and analysis

Separate waste sampling and analysis were conducted for each of the investigated organic waste streams. The investigations were supported by a literature review of existing data for organic waste streams in Chennai. The sampling was conducted at multiple locations in Chennai. For the waste sampling, the LAGA PN 98 (LAGA 2016) waste sampling standard was followed. The samples were collected in sampling bags which were immediately cooled in ice bags after sampling and transported to the lab where the compositional study was carried out by manual sorting. After sorting, the waste samples were minced in a mincer (La Mineva, A/E12-05) with a sieve size of 3 mm. The minced samples were stored at a temperature of + 4 °C. Subsequently, laboratory samples were taken for further chemical analysis and biogas potential test.

VMW, FMW and FMW samples were collected from the city's largest market KWMC. About 50 individual samples of each 5 L capacity were collected from waste heaps in the respective market. Twenty kilograms of SHW was collected from the city's largest slaughterhouse at Perambur, Chennai. It was observed that ruminal contents and blood are the major waste fractions in SHW with 83 wt.-% and 17 wt.-%, respectively. GRW content was collected from a slaughterhouse at Saidapet slaughterhouse. FMW samples (20 kg) were

collected from Saidapet fish market. Around 25 kg of CFW was collected from the canteen of CLRI and analysed for its characterization and composition. CHW samples were collected from an abattoir shop located in Kotturpuram, Chennai. CHW was mixed based on waste generation proportions. From the average of 10 chickens slaughtered, it was observed that 32.5 wt.-% remains as waste, which consists of feathers and skin (57.37 wt.-% of CHW); intestines (20.35 wt.-%); legs (14.8 wt.-%); and others (< 1 wt.-%), which is comparable with the reported waste generation of about 37 wt.-% as CHW (Adhikari et al. 2018; Meeker and Hamilton 2006).

Chemical analysis

The laboratory samples were analysed for dry matter, organic dry matter and moisture content according to APHA (1998). Proteins, lipids and carbohydrates were estimated following Bradford (1976), Frings and Dunn (1970) and Dubois et al. (1956), respectively. Additionally, elemental analyses of the samples were estimated using a CHNS analyser (EA 3000, EURO VECTOR) according to ASTM D5373 (ASTM 2014). Fibre analysis was carried out following Van Soest et al. (1991). Hemicellulose was calculated by the differences of Neutral Detergent Fibre (NDF) and Acid Detergent Fibre (ADF).

Biogas potential test

The biogas potential test was carried out using anaerobic batch tests in 600 mL reactors following VDI-Guideline 4630 (VDI-Guideline 4630 2006). The substrate to inoculum ratio was maintained as 0.5 (g oDM of substrate/g oDM of inoculum). The test was carried out for a period of 30 days. The pressure within the reactor was measured using manometer (EXTECH 407910) and converted into mL_N of biogas produced at standard temperature and pressure conditions. The measured specific biogas yield (SBY) is expressed in terms of mL_N of biogas per g oDM of substrate added. The inoculum was collected from the anaerobic digester of a sewage treatment plant in Chennai, which has 3.8 wt.-% DM, 2.5 wt.-% oDM, and pH of 7.2. The biodegradability of wastes after AD process was measured in terms of oDM reduction.

Biogas potential (m^3/day) for each hotspot was calculated by multiplying the quantity of waste generation with the respective biogas potentials of hotspots. For the estimation of biogas potential density of the hotspot, the total biogas potential of the hotspot was divided by the effective area of the hotspot and the results are presented in Table 3.

GIS mapping of bio-reserves

The GIS methodology follows three steps to evaluate spatial relationships of the waste hotspot/bio-reserves. This study used the QGIS v. 2.18 software as a platform for analysis. In the first step, a thematic layer of the location of major hotspots of bio-reserves and administrative wards in Chennai was created in the GIS interface, representing the current scenario and trends in the city. The point thematic layer with vector points corresponding to the location of vegetable markets, fruit markets, chicken shops, fish markets, canteens and flower markets was plotted. The administrative wards were mapped as polygons with population information and household data. The major organic waste generation point sources are identified as hotspots. In the second step, a circular polygon with a radius of 5 km was superimposed on a selected hotspot, which was selected as maximum feasible waste transportation distance. This effective area is defined as the area that waste disposal trucks can easily travel to obtain different types of waste. The wards in this area were extracted using vector intersection geo-processing. Assuming a uniform distribution of waste in the ward, the waste generated in the parts of the ward superimposed was calculated. The other hotspots lying in the area are also selected for the next step. The last step consisted of the extraction of the processed data of superimposed administrative wards and bio-reserve centres into a table. This data was further used to find improved substrate management possibilities.

Hotspot analysis for improved substrate management

The method of hotspot analysis was done by using the resultant data from the GIS maps of individual hotspot which were extracted into a table that consists of type of organic waste within the hotspot, quantity of wastes, biogas potentials, distance matrix etc. This in turn helps to determine the changes in the C/N ratio and biogas potential during inclusion of wastes from the surrounding 5 km radius with the hotspot as centre point. The distance matrix analysis of GIS allowed for proper inclusion or exclusion of bio-reserves based on the substrates' nutrient balance depending on distance and ease of access.

For carrying out the interpretation of the extracted table from the GIS tool, the following mathematical calculation was used.

Hotspot C/N ratio (with surrounding bio−reserves)

$$= \sum_{i=0}^{n} \left[W_i * (C/N)_i \right] \quad (1)$$

Hotspot biogas potential (with surrounding bio−reserves)

$$= \sum_{i=0}^{n} \left[W_i * BP_i \right]$$

$$(2)$$

where W_1, W_2, W_3,...W_n—Weight of individual waste lying in that hotspot and surrounding bio-reserves; BP_1, BP_2, BP_3,… BP_n—Biogas potential of the corresponding waste; $(C/N)_1$,

$(C/N)_2$, $(C/N)_3$…$(C/N)_n$—C/N ratio of the corresponding waste.

Similarly the C/N ratio of the hotspot with ROW and bio-reserves were calculated by including the quantity of ROW available in the hotspot area with its corresponding C/N ratio using the above expression. Thus, the changes in the biogas potential, C/N ratio, oDM reduction etc. in all the hotspots with and without considering ROW and bio-reserves were observed by using the above equations (Eqs. 1 and 2). The calculated values of C/N ratio and biogas potential of hotspot with and without ROW and bio-reserves were analysed and the optimal solution was provided by means of nearby bio-reserves inclusion or exclusion (by means of transporting the waste) from a hotspot to the nearby hotspots. The outcome of the hotspot mapping was thus used for hotspot analysis for improving the C/N ratio, which in turn improve the process conditions during AD.

The purpose of hotspot analysis in this study is to compare the prevailing waste quantities and optimum process conditions for enhanced biogas production and to minimize the inhibitions during AD of mono-substrate. The results of hotspot analysis help to improve the C/N balance of the major hotspot, which in turn will improve the substrate management, by inclusion or exclusion of the nearby co-substrates. The detailed biogas potentials of individual hotspots, with and without ROW by including nearby bio-reserves within the hotspot of 5 km radius and their corresponding C/N ratio are presented in the "Improved substrate management of Bio-reserves" section.

Results and discussion

Characteristics of organic wastes Bio-reserves in Chennai city

The waste characteristics of various organic wastes in terms of Moisture, Dry Matter (DM), Organic Dry Matter (oDM), Protein, Lipid, Carbohydrates, Neutral Detergent Fibre (NDF), Lignocellulosic Matter (LCM), Nitrogen-free Extract (NfE), Hemi–Cellulose (HC) and Carbon/Nitrogen (C/N ratio) are presented in Table 2. The results of biogas potential test in terms of Specific Biogas Yield (SBY), and oDM reduction after batch AD tests are also presented (Table 2).

As shown in Table 2, moisture content of the wastes varied in the range of 66.7–90.9 wt.-%. The oDM out of DM varied between 71.6–94.1 wt.-%. The higher share of organic fractions and moisture content showed its suitability for AD process (Yan et al. 2017; Mir et al. 2016; Anjum et al. 2012). The carbohydrate content varied between 544.5–702.2 g/kg of DM for VMW, FRW, FLW, BP and CFW whereas found low for FMW (97.8 g/kg) and CHW (141.6 g/kg), since the latter contain higher amount of proteins and lipids in

comparison. The higher NDF of substrates attributed to the higher amount of carbohydrates. Further, it is observed that FRW samples have the highest hemicellulose share of 62.6 wt.-% of NDF, whereas for other wastes, it lies between 35.5–48.0 wt.-%. The C/N ratio is one of the parameters determining the substrates' suitability for the AD process and the optimum values are reported to be 20–30. Both higher and low C/N ratios inhibit biogas production; the former due to rapid acidification and the latter due to ammonia inhibition (Rabii et al. 2019). The C/N ratio of BP and SHW was in the optimal range, but the C/N ratio of VMW, FRW, FLW and CFW ranged from 16.7 to 19.0. However, the C/N ratio was less than 7 for FMW and CHW making it more vulnerable to ammonia inhibition (Wang et al. 2014).

The highest SBY obtained from SBY tests was 514.2 mL_N/g oDM with 61.1 wt.-% oDM reduction for FMW was still lower than the reported range of values, varying from 672.4 to 753.0 mL_N/g oDM with oDM reduction of 77 wt.-%, which could be attributed to the low C/N ratio of FMW (Mshandete et al. 2004; Kafle and Kim 2012). CHW showed the second highest SBY of 480.3 mL_N/g oDM (equivalent to 45.9 L/kg of waste) which is comparable with reported SBY of CHW of 50–60 L/kg of waste by Malayil et al. (2019). The third highest SBY was observed for FRW as 437.9 mL_N/g oDM with oDM reduction of 61.5 wt.-%. This higher yield compared to other carbohydrate-rich substrates (VMW, BP) could be due to the presence of high hemicellulose content (62.6 wt.-% of NDF). The SBY of 435.1 mL_N/g oDM with oDM reduction of 59.7 wt.-% was obtained for CFW, which is in the reported range of 409.8–489.9 mL_N/g oDM (Chen et al. 2014; Yong et al. 2015). The SBY of VMW was 428.8 mL_N/g oDM with oDM reduction of 57.5 wt.-%. Similar results were reported by several authors with SBY in the range of 196–697 mL_N/g oDM (Patil and Deshmukh 2015; Velmurugan and Ramanujam 2011; Mozhiarasi et al. 2019; Kafle et al. 2014).

The SBY obtained for SHW was found to be 309.30 mL_N/g oDM, which is low due to the presence of complex lignocellulose compounds contributed by the large share of ruminal contents that leads to poor biodegradability of the substrates (Jensen et al. 2016). The SBY of BP was 250.4 mL/g DM (equivalent to 331.6 mL_N/g oDM), which is comparable with the reported biogas potential of banana waste as 271 mL_N/g DM by Kalia et al. (2000).

Lower SBY was obtained for FLW and GRC, which were 240.2 mL_N/g oDM and 277.5 mL_N/g oDM with oDM reduction of 36.4 wt.-% and 41.3 wt.-%, respectively. Kulkarni and Ghanegaonkar (2019) studied the biogas potential of different FLW and reported to be in the range of 78.9–101.8 mL_N/g DM with oDM reduction of 45 wt.-% (Kumar and Swapnavahini 2012) which was lower than the yield obtained in this study (215.1 mL_N/g DM). Further, Kumar and Swapnavahini

Table 2 Waste characterization and specific biogas yield of organic waste bio-reserves in Chennai city

Parameter	Units	VMW	FRW	FLW	BP	GRC	SHW	FMW	CHW	CFW	ROW*
Moisture	wt.-%	90.9	87.8	77.6	90.6	82.9	72.8	80.7	66.7	70.8	75.3
DM	wt.-%	9.1	12.2	22.4	9.4	17.1	27.2	19.3	33.3	29.2	24.7
oDM	wt.-%	8.1	11.2	20	7.1	15	19.5	16.5	30.4	27.5	19.4
Carbohydrates	g/kg of DM	676.2	702.2	575.7	689.4	442.6	313.9	97.8	141.6	544.5	–
Protein	g/kg of DM	127.4	131.2	157.3	57.2	176.8	251.1	510.9	462.4	143.6	–
Lipid	g/kg of DM	57.4	61.1	78.9	11.2	154	131.1	222.8	219.7	84.1	–
NDF	g/kg of DM	431.5	444.6	549.8	522.1	427.4	303.6	71	138.2	442.1	–
Lignocellulosic matter	g/kg of DM	278.5	166.4	297.6	320.4	283	227.2	58	81	230	
Nitrogen-free extract	g/kg of DM	276.1	276.4	108.5	166.7	283	227.2	50.2	92.6	271.9	–
Hemicellulose	g/kg of DM	153.0	278.2	252.2	201.7	144.4	76.4	13.0	57.2	212.1	–
HC/NDF percent	(%)	35.5	62.6	45.9	38.6	33.8	25.2	18.3	41.4	48.0	–
C/N ratio	–	16.7	18.9	17.6	26	12.6	21.5	5.7	6.9	19	22.4
Specific Biogas Yield	mLN/g oDM	428.8	437.9	240.2	331.6	277.5	309.3	514.2	480.3	435.1	303.4
oDM reduction	%	57.5	61.5	36.4	50	41.3	44.6	61.1	53.8	59.7	60.7

*Source: Mondal et al. (2016); Dhar et al. (2015)

(2012) observed 32.6% increase in the biogas yield during co-digestion with food waste.

Dhar et al. (2016) evaluated the biogas potential of organic fractions of MSW and results revealed that the SBY as 303.4 mL$_N$/g oDM with 60.7 wt.-% oDM reduction, which was taken for the estimation of SBY potential of ROW from different wards of Chennai city. This is comparable with the other reported literature values in the range of 215–540 mL$_N$/g oDM (Pavi et al. 2017; Jørgensen 2009; Dasgupta and Mondal 2012).

GIS mapping of bio-reserves hotspots

The hotspots of bio-reserves are plotted in Fig. 2.

In Fig. 2, the Chennai Corporation wards are displayed with their daily contribution of waste, including the bio-reserves availability in the ward, in kg/km^2/day. The hotspots of bio-reserve were surveyed mainly in the Chennai's central region. The irregular border on right indicates shoreline whereas on the left indicates district boundary with other districts (Figs. 2, 3 and 4). As for the population density, the peripheral areas show lower population density compared to central and hence lower waste generation, which is displayed using lighter shade. Including the waste generated from bio-reserves, the map has a concentrated waste generation in ward 127 due to KWMC. It can also be observed that the concentration of waste in ward 142 and nearby region can be attributed to the high population density in the area along with fish market, vegetable market and slaughterhouse at Saidapet. The wards farther south show a similar trend around Thiruvanmiyur market (ward 180).

The biogas calculation, using the residential organic waste and bio-reserves, revealed that the total biogas potential from the study area of major hotspots of Chennai is equal to 125,871.2 m^3/day. The highest biogas potential density is estimated in ward 75 (1985.08 m^3/km^2/day) followed by ward 51 (1912.03 m^3/km^2/day) due to high population density and small areas (Fig. 3). The next two highest biogas potential density comes from wards 127 (1725.76 m^3/km^2/day) and 142 (1585.23 m^3/km^2/day) which include major organic waste generation hotspots like Koyambedu market and Saidapet market, respectively. The other wards have distributed biogas densities with 23 wards in the range of 0–100 m^3/km^2/day, 31 wards in 100–200 m^3/km^2/day, 24 wards in 200–300 m^3/km^2/day, 28 wards in 300–400 m^3/km^2/day, 21 wards in 400–500 m^3/km^2/day, 26 wards in 500–600 m^3/km^2/day, 13 wards in the 600–700 m^3/km^2/day, 7 wards in 700–800 m^3/km^2/day, 9 wards in 800–900 m^3/km^2/day, 5 wards in 900–1000 m^3/km^2/day, 1 ward in the 1000–1100 m^3/km^2/day, 3 wards in 1100–1200 m^3/km^2/day, 1 ward in 1200–1300 m^3/km^2/day, 3 wards in 1300–1400 m^3/km^2/day, 3 wards in 1500–1600 m^3/km^2/day, 1 ward in 1700–1800 m^3/km^2/day and 2 wards in 1900–2000 m^3/km^2/day.

Improved substrate management of Bio-reserves

In Fig. 4, the effective areas of major waste generating spots from where the waste can be conveniently procured for the biogas plant input are presented.

It was observed that the maximum potential lies in the area near Koyambedu market (Fig. 4a). The biogas potential and its density, with and without considering ROW and, bio-reserves in the range of 5 km radius with hotspot as centre are presented in Table 3.

Fig. 3 Histogram of ward-wise total biogas potential density
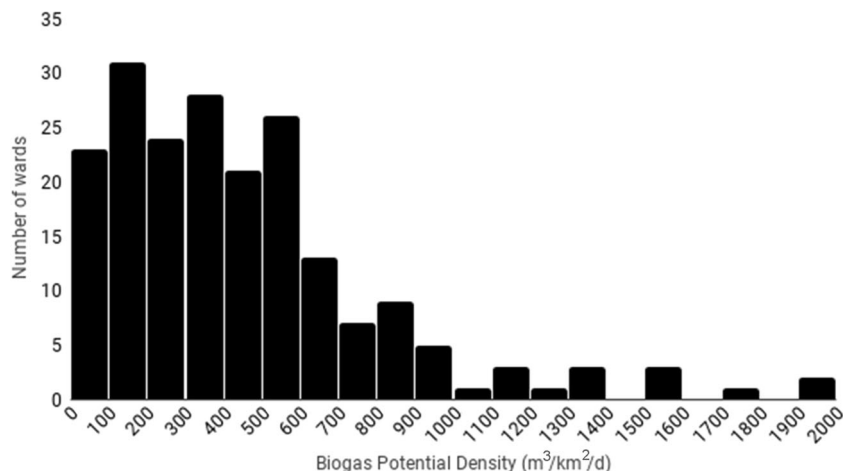
Hotspot of Koyambedu market

The estimated biogas potential of Koyambedu market hotspot alone is 5938.7 m³/day with C/N ratio of 20.0 from 170.0 tons of wastes in the Koyambedu market. This hotspot has yielded the highest biogas potential in comparison with other hotspots studied, which is due to the high amount of waste quantities available in this area.

In this hotspot, if ROW and available bio-reserves within 5 km radius were considered, then the biogas potential is estimated as 32,424.6 m³/day with C/N ratio of 21.7, while

considering Koyambedu hotspot alone. This increase was due to the increase in the waste generation quantities from 170.0 to 620.0 tons while considering ROW and bio-reserves (Table 3). The proportion of wastes while considering ROW and bio-reserves within 5 km radius are as follows: 72.5 wt.-% ROW; 12.3 wt.-% VMW; 8.2 wt.-% BP; 6.3 wt.-% FRW; 0.5 wt.-% FLW; 0.1 wt.-% of both SHW and CHW (Fig. 5).

In another scenario, if ROW is neglected and, only the wastes from the hotspot and the surrounding bio-reserves are considered, then the biogas potential slightly increases to
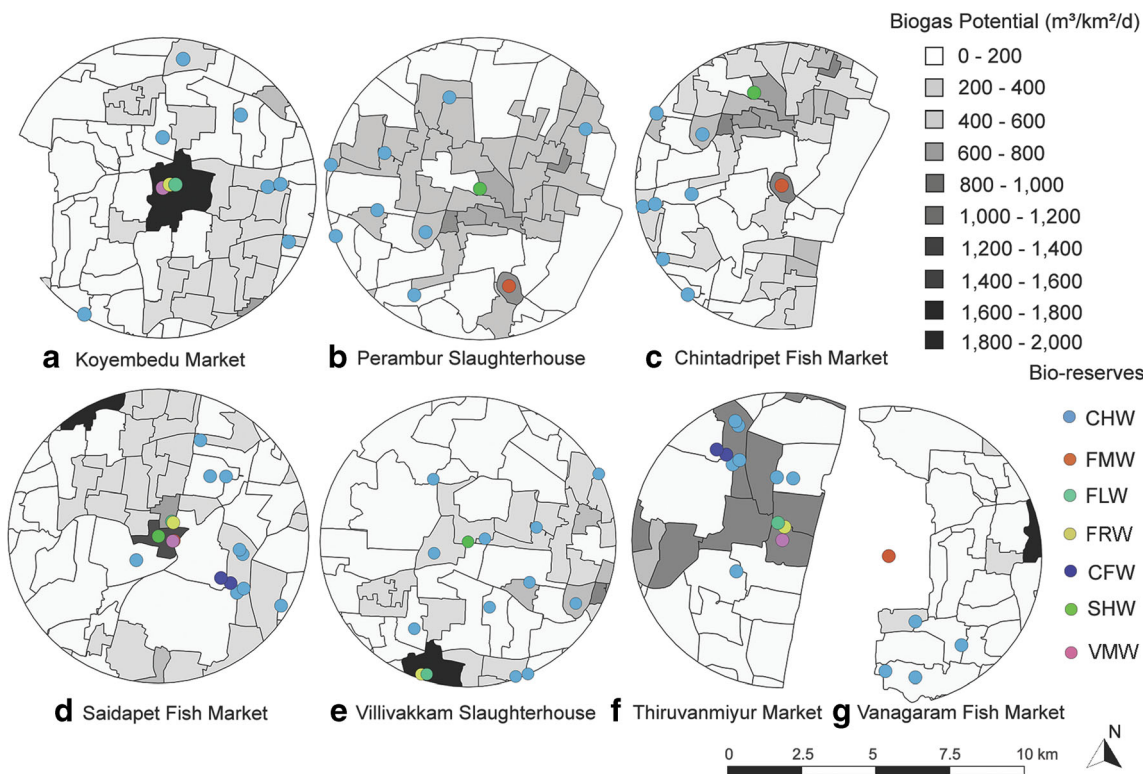

Fig. 4 Bio-reserves within 5 km radius from the hotspots

Table 3 Waste generation amounts and biogas potential of hotspots alone, with bio-reserves, with and without ROW

Hotspots	Hotspot alone		Hotspot with bio-reserves and ROW		Hotspot with bio-reserves and without ROW	
	Waste generation (tons/day)	Biogas potential (m³/day)	Waste generation (tons/day)	Biogas potential (m³/day)	Waste generation (tons/day)	Biogas potential (m³/day)
Koyambedu market	170.0	5938.8	620.0	32424.6	170.6	5969
Perambur slaughterhouse	9.0	487.0	612.6	36206.3	14.0	974
Chintadripet fish market	4.0	339.4	548.2	32381.4	13.6	913
Saidapet fish market	10.0	514.2	557.0	32914.2	24.2	1554
Villivakkam slaughterhouse	0.5	20.8	461.6	27204.2	44.5	2651
Thiruvanmiyur market	1.0	38.1	302.9	17925.7	2.7	253
Vanagaram fish market	2.5	212.1	144.0	8597.6	3.2	307

5969.5 m³/day (0.5% increase than considering hotspot alone) originating from 170.6 tons of wastes with C/N ratio of 20.0 in the following proportions: 44.8 wt.-%VMW; 29.9 wt.-% BP; 22.9 wt.-% FRW; 1.9 wt.-% FLW; 0.3% SHW; 0.04% CHW.

In both the cases i.e. with and without ROW, the C/N ratio of wastes surrounding the hotspot altogether results in the C/N ratio in the optimal range. Hence, in this hotspot, all the projected nearby bio-reserves could be collected and utilized for biogas generation.

Hotspot of Perambur slaughterhouse

For the hotspot of Perambur slaughterhouse, the biogas potential of hotspot alone is 487.0 m³/day from 9.0 tons of SHW, with C/N ratio of 21.5 (Table 3). In this hotspot, if both ROW and surrounding bio-reserves are considered, then the estimated biogas potential is 36,206.3 m³/day, resulting from 612.6 tons of wastes. In this scenario, the C/N ratio increases to 22.3 even though the C/N ratio of individual wastes varies

Fig. 5 Proportions of bio-reserves in hotspot with and without ROW
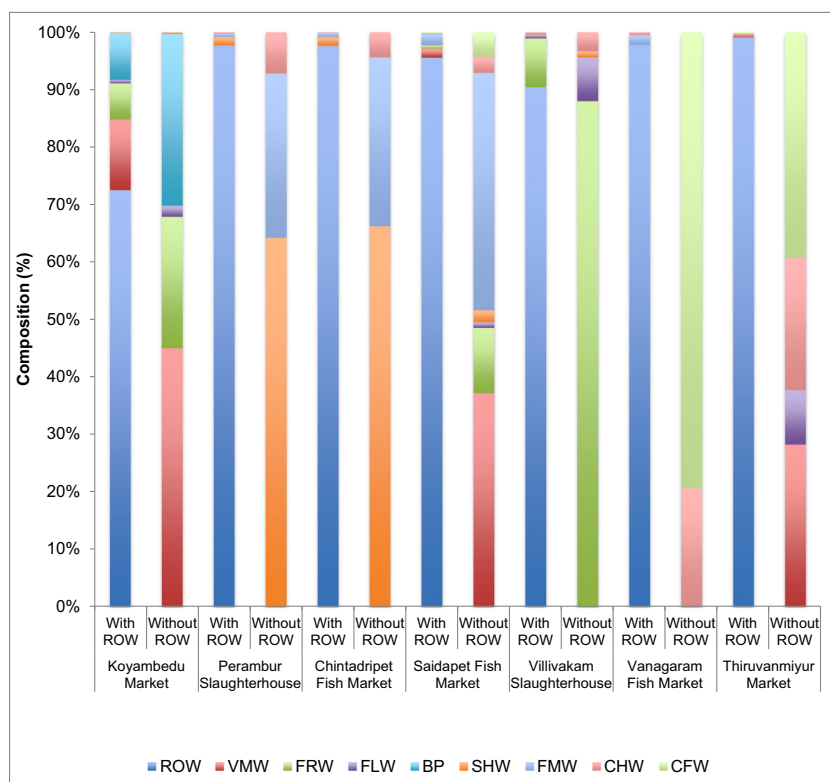
in the range of 6.9–22.4. This is due to the higher share of ROW of 97.7 wt.-% (Fig. 5) if both ROW and bio-reserves are considered.

In this hotspot, while considering the surrounding bio-reserves and excluding ROW, the biogas potential is estimated to be 974.1 m^3/day originating from 14.0 tons of wastes (Table 3). In this scenario, the C/N ratio reduces to 15.9, which is not optimal for AD.

If CHW is eliminated, then the C/N ratio will increase slightly to 16.6 since its share in this hotspot is comparatively lesser (7.2 wt.-% CHW < 28.5 wt.-% FMW) than FMW (Fig. 5). Hence, eliminating CHW does not have greater influence in C/N ratio. So, in this scenario, the collection of FMW from Chintadripet fish market has to be eliminated, although it is located within 5 km of this hotspot with higher SBY (7.1 vol.-%) than CHW. This is mainly due to its low C/N ratio of FMW of 5.7. In order to maintain the C/N balance, the following proportions can be maintained, 89.9 wt.-% SHW; 10.1 wt.-% CHW, which could yield the C/N ratio of 20. The resulting biogas potential will be 634.8 m^3/day from 10.0 tons of wastes.

Hotspot of Chintadripet fish market

The estimated biogas potential of hotspot of Chintadripet fish market is 339.4 m^3/day originating from 4.0 tons of waste with C/N ratio of 5.7. While including ROW and nearby bio-reserves, then the biogas potential of Chintadripet fish market hotspot increases to 32,381.4 m^3/day from 548.2 tons of wastes with the C/N ratio of 22.2.

On excluding ROW and including the bio-reserves, the biogas potential is estimated as 913.1 m^3/day from 13.6 tons of wastes with C/N ratio of 16.2. The C/N ratio is below the optimal range due to large share of FMW of 66.2 wt.-% (Fig. 5). In order to balance the C/N ratio, if CHW is neglected, the C/N ratio of this hotspot slightly increases to 16.6. On the other hand, if SHW has been neglected, then the C/N ratio will reduce further to 5.9. Hence, in this case, the solution could be the reduction of FMW quantity from 4.0 to 0.4 tons, which will yield a C/N ratio of 20, originating from 10.0 tons of wastes. The mixing ratio in this scenario will be as follows: 6.0 wt.-% CHW; 4.0 wt.-% FMW; 90.0 wt.-% SHW.

However, the excluded 3.6 tons of FMW needs to be treated and hence, the solution could be the transport of this waste to the Koyambedu market, since all the wastes in the Koyambedu hotspot have better C/N balance. In addition to C/N balance, the distance between these two hotspots is 8.1 km, which is almost closer to each other, although it exceeded the distance fixed up as 5 km in the current study. In this scenario, the biogas potential of Koyambedu market hotspot increases from 5969.5 m^3/day to 6274.9 m^3/day due to the addition of 3.6 tons of FMW to the Koyambedu hotspot.

This addition of FMW result in the C/N ratio of 19.7 from 20.0 but it is still closer to optimal range for AD.

Hotspot of Saidapet fish market

The biogas potential of Saidapet fish market alone is estimated as 514.2 m^3/day originating from 10.0 tons of fish market waste, with C/N ratio of 5.7. For this hotspot, if ROW and nearby bio-reserves are considered, then the biogas potential further increases to 32,914.2 m^3/day from 557.0 tons of wastes, with C/N ratio of 22.0, which is in the optimal range.

The biogas potential of surrounding bio-reserves in this hotspot, by excluding ROW, is 1554.1 m^3/day from 24.2 tons of wastes with C/N ratio of 12.2 which is less than the optimal range. This is due to large shares of FMW of 41.3 wt.-%. There is no improvement in the C/N balance even if CHW has been removed, since it contributes only 2.8 wt.-% to the bio-reserves share. Hence, the suitable substrate management option could be to transfer 10.0 tons of FMW from Saidapet fish market to the Koyambedu market hotspot (distance between these two hotspots is 6.1 km), which will result in the C/N ratio of 19.2, which is in close proximity with the optimal C/N value. As a result, the biogas potential of Koyambedu market will increase from 5969.5 m^3/day to 6817.9 m^3/day, due to the increase in quantity of wastes from 170.6 to 180.6 tons.

Hotspot of Villivakkam slaughterhouse

The biogas potential of Villivakkam slaughterhouse hotspot is 20.8 m^3/day resulting from 0.5 tons of SHW. Similar to other hotspots, with addition of ROW and bio-reserves, the resultant C/N ratio is 22 with the biogas potential of 27,204.2 m^3/day from 461.6 tons of wastes.

While considering the nearby bio-reserves by excluding ROW, then the C/N will remain as 18.3, which is slightly lesser than the optimal range, with the estimated biogas potential of 2651.4 m^3/day from 44.5 tons of wastes. Even, if CHW is removed from the bio-reserve, there is no significant change in the C/N ratio because of its minimal share (3.3 wt.-%), as the C/N of major wastes (> 95%) ranges between 17.6 and 18.9. Hence, for this hotspot, all the bio-reserve falling under this area can be considered for biogas generation.

Hotspot of Vanagaram fish market

The biogas potential of Vanagaram fish market alone is 212.1 m^3/day with C/N ratio of 5.7 resulting from 2.5 tons of fish waste generation. This hotspot also has balanced C/N ratio of 22 while considering the ROW with the biogas potential of 8597.6 m^3/day originating from 144.0 tons of wastes.

In this hotspot, if ROW is neglected and only the bio-reserves are considered, then the resulting C/N ratio is 5.9

due to larger shares of FMW of 79.4 wt.-% and CHW of 20.6 wt.-%. The resultant biogas potential is 307.0 m^3/day from 3.15 tons of wastes (Fig. 5). This will lead to process inhibitions due to the poor substrate composition. Hence, for this hotspot, similar to other fish market hotspots, it is highly recommended to transport this fish market waste to the Koyambedu market hotspot. In this scenario, the C/N ratio of Koyambedu hotspot slightly reduces from 20.0 to 19.8 and the biogas potential increases from 5969.5 m^3/day to 6181.6 m^3/day, due to the increase in the waste quantities from 170.6 to 173.0 tons.

Hence in order to obtain optimal C/N balance, the effective substrate management solution could be the transportation of 3.6 tons of FMW from Chintadripet fish market, 10.0 tons from Saidapet fish market and 2.5 tons from Vanagaram fish market to the Koyambedu hotspot. In this scenario, the increase of 16.1 tons of FMW from these 3 markets to the Koyambedu hotspot will result in a C/N ratio of 18.8, which is slightly less than the optimal. But still there is an improvement of C/N ratio from 5.7 (FMW) to 18.8 (combined wastes) which could reduce the operational problems due to low C/N ratio. However the addition of 16.1 tons of FMW increases the biogas potential of Koyambedu market from 5969.5 m^3/day to 7335.5 m^3/day.

Hotspot of Thiruvanmiyur market

In this hotspot, if only wastes from Thiruvanmiyur vegetable market are considered, then the biogas potential is 38.0 m^3/day with C/N ratio of 16.9. However, if ROW and surrounding bio-reserves are considered, then the biogas potential increases to 17,925.7 m^3/day resulting from 302.9 tons of wastes. In this scenario, the resultant C/N ratio is 22.3, which is optimal for AD.

If ROW is not considered, then the C/N ratio reduces to 15.4 due to large shares of CHW of around 23.1 wt.-% and the resulting biogas will be 253.2 m^3/day from 2.7 tons of wastes. Since the C/N ratio is lesser than optimal, it can be increased to 18 if CHW is not collected.

Bio-reserves management in urban areas (Chennai)

From the investigation of major organic waste generating hotspots in urban areas, it can be observed that there exists huge availability of potential waste resources (VMW, FRW, FLW, BP, FMW, CHW, CFW, ROW and SHW) with varying characterization, biogas potential and nutrient availability. It can be observed that the lower C/N ratio is mainly attributed to the large shares of CHW and FMW in a particular hotspot. Whereas the higher C/N ratio is mainly contributed by large shares of ROW, BP, CFW and VMW. This can be illustrated using the Vanagaram fish market hotspot where the C/N ratio with and without ROW is recorded as 22 and 5.9, respectively.

For efficient substrate management of the wastes from fish markets, the optimal solution identified in this study is to utilize the FMW from Chintadripet, Saidapet and Vanagaram fish market along with Koyambedu market hotspot, which not only improves the substrate management for fish wastes but also shows increase (22.9%) in the biogas potential of the Koyambedu hotspot with improved C/N ratio from 5.7 to 18.8.

From the major hotspots studied, it can be observed that the location of major hotspots and the spatial relationship with potential bio-reserves around it are important in the establishment of biogas plants and increasing the energy outputs. It also facilitates improved substrate management in a way that it distributes macro-nutrients by balancing protein, lipids and carbohydrate contents along with balancing C/N ratio, thereby reducing process inhibitions like VFA, ammonia etc. This eventually enhances the performance and stability of the digester (Wang et al. 2014).

Also, it was found that the initial oDM value of wastes at various hotspots increased from 17.6 to 171.6 wt.-% while considering the different nearby organic waste bio-reserves within 5 km radius of the hotspot. The oDM reduction was also improved while mixing different substrates within the hotspot in addition to the balanced distribution of macro and micronutrients. For Koyambedu hotspot, significant variations in the oDM reduction of the individual wastes between 36.4–61.5 wt.-% were observed, whereas oDM reduction after substrate management narrows down to 55.7–59.3 wt.-%. Similar improvements in the oDM reduction were observed for other hotspots. This clearly shows that the substrate management could be significantly improved by utilizing bio-reserves of the surrounding hotspot.

Overall, the current study identified the location of major waste generating hotspots and the possibility of utilization of the nearby co-substrates for improved substrate management for anaerobic digestion process based on the surrounding substrate's availability, characteristics, quantities and its biogas potentials. This results in the improved process and digester stability, consistent oDM removal efficiency and enhanced biogas production. Further, the study illustrates the potential for successful implementation of substrate management with GIS as a decision-making tool for establishing decentralized biogas plants in urban centres.

A way towards integrated urban substrate management and the existing government policies

Moving forward, the prepared interactive map of organic waste bio-reserves in various major waste generating hotspots of Chennai city could be utilized by the municipal corporation/stakeholders to meet the urban waste management goals such as Swachh Bharat Mission, Smart Cities, Sustainable Development Goals (SDG) of United Nations etc. The waste to energy system would be economically feasible only if the

government incentives are taken into account to balance the initial high capital costs. However, the technological barriers in the dissemination of biogas technology in Chennai city can be minimized by integrated urban substrate management system proposed in this study. Although partial efforts are being made by the municipal corporation of Chennai city for the management of solid waste through setting up of compost plants/smaller capacity biogas plants, still the major issue is the under-exploitation of wastes' potency for energy production rather than converting it as fertilizer whose market value is low in an urban city. On the other hand, it is highly uneconomical to install monitoring system, engage skilled manpower, purify/ upgrade biogas system for installation and operation of smaller capacity biogas plants. Hence, treatment of waste through anaerobic co-digestion in the major waste generating hotspots would benefit to meet the rising energy demand of Chennai city as well as solves the barriers in biogas technology. In urban cities of India, it is reported that the major constraint for the establishment of biogas plants is finance as that almost 3/4th of the cost allocation for solid waste management is being spent for collection and transportation of wastes itself (Lahiry 2019). Hence, the establishment of biogas plants in the major waste generating hotspots itself can reduce the transportation cost and the saved cost could be potentially utilized for setting up of biogas plants in the major waste generating hotspots of Chennai city. Further, hotspot mapping of waste bio-reserves not only overcomes the limitations of exposing the resource availability but also helps better data interpretation for effective decision-making and thus pays a way towards sustainable and integrated solid waste management globally by anaerobic co-treatment system.

Conclusion

The present study investigated the major waste generating hotspots in Chennai city and estimated the biogas potential of various organic fractions of MSW. The biogas potentials of various bio-reserves considered in this study ranged between 240.2–514.2 mL$_N$/g oDM with oDM reduction in the range of 36.4–61.5 wt.-%. The results of organic waste bio-reserves survey were plotted as hotspots of bio-reserves using GIS mapping. The results of GIS plots showed that, among the 200 wards in the Chennai city, the organic waste density is found to be majorly concentrated in the wards of 51, 75, 127, 142 and 180 attributed to the nearby regions of major hotspots such as Perambur slaughterhouse, Koyambedu market, Saidapet fish market/slaughterhouse and Thiruvanmiyur market. Results of histogram of ward-wise biogas potential density revealed that the higher biogas potential density in the range of 1985.0–1585 m^3/km^2/day is mainly attributed to the regions of Koyambedu market, Perambur slaughterhouse and Saidapet fish market and slaughterhouse. Based on the GIS plots of

bio-reserves and the biogas potentials, the solution for the improved substrate management was suggested by projecting the bio-reserves within 5 km radius of major hotspots. The biogas potential of individual hotspots ranged between 38.0 m^3/day and 5938.7 m^3/day and increases to 253.2 m^3/day–5969.5 m^3/day when surrounding bio-reserves encircling the hotspot of 5 km radius are considered. Further, the biogas potential increases to 4110.4–18,106.1 m^3/day by considering ROW within the 5-km radius including the bio-reserves.

For efficient nutrient balance for the better control of process and operational parameters of AD process such as C/N ratio, macro and micronutrients, oDM reduction etc., an investigation on the improved nutrient balance was conducted by evaluating the various bio-reserves within the hotspots in different combinations and the optimal mixing ratio was evaluated. Among the various major hotspots, the utilization of FMW as a potential bio-reserve has revealed imbalances due to poor C/N ratio. Hence, the optimal solution identified is to utilize the wastes from fish markets along with the Koyambedu market hotspot. This not only improves the C/N balance but also increases (22.9%) the biogas potential of Koyambedu hotspot, thereby a way to handle the various major waste generations in urban centres and also to stabilize the AD process through improved substrate management.

Addition of wastes in the hotspot results in variations of C/N ratio from 5.7 to 18.8, which indicates that the mixing of wastes in 5 km is beneficial in most of the cases except few places like FMW due to the low C/N ratio of fish wastes. This approach of substrate management in urban centres not only increases the biogas potential but also helps in balancing the nutrient availability in different wastes for successful operation of AD plants in urban centres.

The outcome of the present study provides information on the available organic waste bio-reserves in an urban area. This concept of GIS mapping of hotspots of organic waste bio-reserves, characterization and biogas potential estimations could be investigated and potentially utilized in other urban centres of India and in the world which will enable the decision makers to arrive at sustainable waste management plan.

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