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Pyrolysis and co-composting of municipal organic waste in Bangladesh: A quantitative estimate of recyclable nutrients, greenhouse gas emissions, and economic benefits

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ABSTRACT

Waste causes environmental pollution and greenhouse gas (GHG) emissions when it is not managed sustainably. In Bangladesh, municipal organic waste (MOW) is partially collected and landfilled. Thus, it causes deterioration of the environment urging a recycle-oriented waste management system. In this study, we propose a waste management system through pyrolysis of selective MOW for biochar production and composting of the remainder with biochar as an additive. We estimated the carbon (C), nitrogen (N), phosphorus (P) and potassium (K) recycling potentials in the new techniques of waste management. Waste generation of a city was calculated using population density and per capita waste generation rate (PWGR). Two indicators of economic development, i.e., gross domestic product (GDP) and per capita gross national income (GNI) were used to adopt PWGR with a projected contribution of 5–20% to waste generation. The projected PWGR was then validated with a survey. The waste generation from urban areas of Bangladesh in 2016 was estimated between 15,507 and 15,888 t day^{-1} with a large share (~75%) of organic waste. Adoption of the proposed system could produce 3936 t day^{-1} biochar blended compost with an annual return of US $210 million in 2016 while it could reduce GHG emission substantially (−503 CO_2 e t^{-1} municipal waste). Moreover, the proposed system would able to recover ~46%, 54%, 54% and 61% of total C, N, P and K content in the initial waste, respectively. We also provide a projection of waste generation and nutrient recycling potentials for the year 2035. The proposed method could be a self-sustaining policy option for waste management as it would generate ~US$51 from each tonne of waste. Moreover, a significant amount of nutrients can be recycled to agriculture while contributing to the reduction in environmental pollution and GHG emission.

1. Introduction

Waste is generated from our daily household activities, agricultural operations and industrial by-products. Like other developing countries, sustainable waste management in the major cities is a challenging task for Bangladesh. This is because, its municipal waste (MW) management is entangled with numerous problems including a large volume of waste generation, lack of sustainable technologies and policies, and non-compliance of the citizens to waste separation and disposal guidelines. As a result, a large fraction of the MW (~50%) remain uncollected (Mahmud, 2014; Yousuf and Rahman, 2007) and decompose in the open places.

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Hence, city dwellers have been experiencing a number of unavoidable consequences, which include- (a) bad smell of decomposing wastes, (b) diseases such as diarrhoea, dysentery, and eczema, (c) parasite infestation like worm and mosquito, (d) polluted air and water, (e) chronic health risk from persistent organic pollutants and (f) frequent flooding of the cities during summer showers due to clogging of drainage channels (Das et al., 2014; Giusti, 2009; Karn and Harada, 2001; Mahmud et al., 2012; Rafizul and Alamgir, 2012). Therefore, weak waste management policies and inadequate efforts of the municipalities are often strongly criticised. The waste management of the large cities in Bangladesh is even getting tougher due to a continuous increase of the urban population. Although, some of the waste such as plastic, glass and iron are increasingly recycled in recent years (Hoornweg and Bhada-Tata, 2012), the collected organic waste is usually dumped in open places without any sanitary management, which can potentially contaminate ground water (DOE, Waste Concern and ITN-BUET, 2004). The waste, either dumped to canals and rivers or disposed as open landfilling resulted in permanent deterioration of several rivers in Bangladesh including the *Buriganga* near Dhaka. Therefore, it is an urgent need for Bangladesh to reduce pollution and revive the health of rivers by managing waste, particularly the organic waste in sustainable ways.

Waste can be a resource, if it is recycled and reused. Municipal organic waste (MOW) can be recycled or managed through composting, anaerobic decomposition and biogas generation, incineration, sanitary dumping etc. However, none of these strategies either singly or in combination has been adopted largely in Bangladesh possibly due to inherent limitations of the strategies or lack of awareness or collective initiatives. Recently, pyrolysis of waste biomass is also advocated elsewhere in the world, but it is not explored yet in Bangladesh. Moreover, handling high volumes of waste is challenging for all of these strategies. A combination of several strategies might be more efficient and provide sustainable solutions (Singh et al., 2011).

Municipal organic waste contains varieties of solid and semi-solid waste which can potentially be separated into target bound fractions, for example, (a) compostable, (b) pyrolysable and (c) fuel for pyrolysis considering the state of collection and type of waste. Thus, a fraction of separated waste can be composted while a self-sustaining pyrolysis plant can be run with the other two fractions, i.e., a part of dried biomass can be used for generation of heat for pyrolysis of the other part and the heat generated from pyrolysing biomass can be recycled to accelerate the pyrolysis process (Mia et al., 2015). In addition, use of biochar as additive to compost can increase both biochar and compost quality (Steiner et al., 2010; Wiedner et al., 2015; Wu et al., 2016; Zhang et al., 2014a).

1.1. Synergies of biochar blended composting

Biochar is pyrolysed biomass and contains a variable proportion of aromatic and aliphatic carbon (C). It has large specific surface area and often carries surface charges, which can potentially contributes to nutrient retention (Mia et al., 2017a). When used as an additive to composting biomass, biochar could provide several synergistic benefits (Fischer and Glaser, 2012) (Fig. 1). Firstly, microbial degradation of biomass is accelerated by a high temperature (~70 °C) during the bio-oxidation phase of composting (Cáceres et al., 2016; Dias et al., 2010) and accelerated growth of microorganisms that is supported with biochar's refugee sites (Jindo et al., 2012; Sun et al., 2016). Secondly, biochar acts as a bulking agent which increases aeration within the compost pile (Steiner et al., 2010). In addition, biochar adsorbs organic matter on its surfaces (LeCroy et al., 2013), which increases co-mineralisation of biochar, particularly the labile fraction (Hamer, 2004). Thus, co-composting of biochar with biomass accelerates both composting and mineralisation of biochar. However, the mineralisation of biochar and its effects on composting depends on biochar quality, microbial activity and temperature of the composting pile (Li et al., 2015).

Mineralisation of organic nitrogen (N) from fresh biomass increases N concentration in the composting pile. A significant part of the mineral N is lost through gaseous losses during composting. A part of the N can be adsorbed as NH_4^+ and NO_3^- onto fresh biochar (Kammann et al., 2015; Mizuta et al., 2004). The increased N reduces the labile C:N ratio, which could further accelerate the composting process (Khan et al., 2014) and the time for composting is shortened (Sánchez-García et al., 2015). The accelerated decomposition could

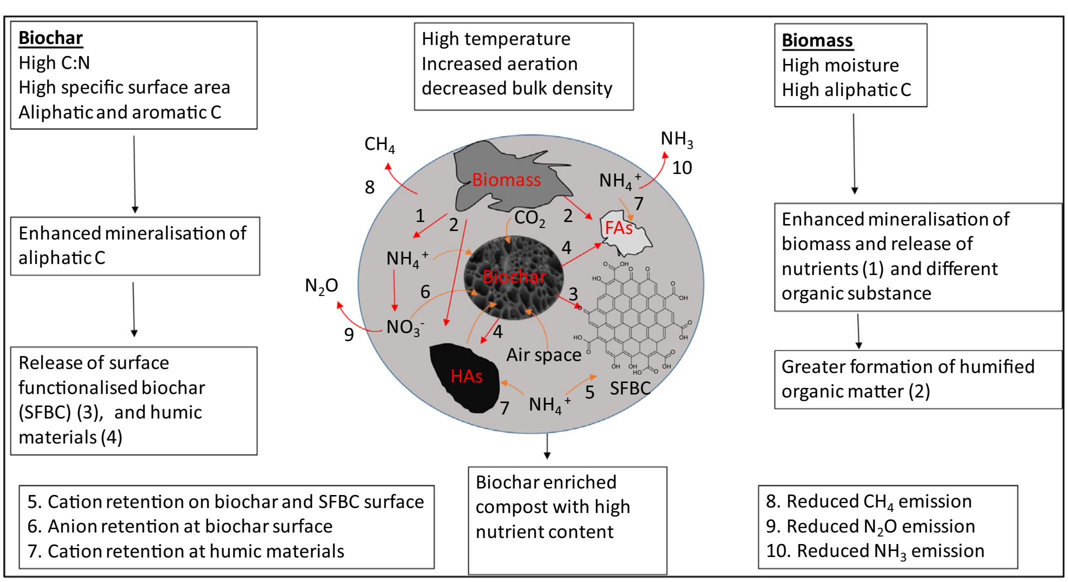

Fig. 1. Schematic diagram of changes in biochar and biomass properties, retention of nutrients and reduction of greenhouse gas emissions during co-composting of biochar with biomass. HA and FA indicates Humic acids and Fulvic acids, respectively. The proposed mechanisms are based on the findings of Agyarko-Mintah et al. (2017), Dias et al. (2010), Hijikata et al. (2015), Mia et al. (2017a,b), Jindo et al. (2012), Kammann et al. (2015), Mizuta et al. (2004), Sanchez-Monedero et al. (2018), Steiner et al. (2010), Zhang et al. (2014b) and Zhang and Sun (2014c).

produce humified organic matter, which could act as effective nutrient retaining agent (Dias et al., 2010; Zhang et al., 2014b). When biochar is mineralised, functional groups such as carboxylic and phenolic groups are developed on its surface leading to an increase in cation exchange capacity that could retain NH_4^+—N (Mia et al., 2017a; Steiner et al., 2010; Wiedner et al., 2015). As result, compost quality is improved due to a high content of nutrients particularly N (Hijikata et al., 2015; Kammann et al., 2015; Zhang and Sun, 2014c). This surface functionalised biochar could provide an opportunity to hold nutrients when applied to the soil while it also retains its role of C sequestration (Mia et al., 2017b).

1.2. Greenhouse gas emission

Municipal waste is one of the dominant sources of greenhouse gas (GHG) emission estimating 18.76% of the total GHG emission in Bangladesh (WRI, 2014). While composting of MW contributes significantly to GHG emissions, these emissions can be reduced significantly if biochar is added to composting biomass (Fig. 1) (Sánchez et al., 2015; Sanchez-Monedero et al., 2018). Although biochar addition can accelerate CO_2 production, it can adsorb CO_2 in its surface area resulting in an apparent reduction of CO_2 emission (Hamer, 2004; Agyarko-Mintah et al., 2017). Similarly, a large reduction of methane (CH_4) emission is reported in the literature with possible attribution of biochar mediated improved aeration (Agyarko-Mintah et al., 2017; Sanchez-Monedero et al., 2018). Emission of nitrous oxide (N_2O), the third most important GHG, has been shown to abate since biochar can reduce inorganic N concentration in the composting mix through adsorption or microbial immobilisation (Sanchez-Monedero et al., 2018). A reduction of anaerobic microsite formation, and enhanced nitrification through changing microbial community also contribute to the N_2O emission reduction (Agyarko-Mintah et al., 2017; Chen et al., 2017; Sanchez-Monedero et al., 2018).

Therefore, recycling of C and nutrients through co-composting of biochar can provide a sustainable mean for increasing agricultural productivity, sequestering C as well as for waste management, when MOW is used. It can also have significant impact on GHG abatement.

The proposed synergistic benefits can also be harvested through biochar production from pyrolysable MOW and co-composting with the compostable part. The ultimate product, biochar blended compost can be used for agriculture to increase C content and nutrient retention capacities in soils (Joseph et al., 2013). Here, we provide a model for MOW management tailoring target-oriented waste separation and simultaneous pyrolysis and co-composting. Additionally, we provide an estimate of potential waste generation, nutrient recycling, GHG abatement, and returns in Bangladesh.

2. Methodology

In this study, we provide an estimation of waste generation, projection of waste generation rate, assessment of physical composition of waste, estimation of recyclable nutrient, GHG emission, and economic returns. We used literature data for our calculations. However, we also used survey data to validate the projected estimation of waste generation. A thematic approach was followed to index the collected literature and use of the information. The publications used for this review are listed in the supporting information (SI, Table S1). The detailed calculation procedure is presented in the following sections.

2.1. Estimation of waste generation

Waste generation of a city can be calculated from the per capita waste generation rate (PWGR) by multiplying with its population size. Municipal waste generation capacities of major cities in Bangladesh were not available or if available, were highly inconsistent. Most of the studies were based on surveys and representation of secondary data (Chowdhury et al., 2014; Das et al., 2014; Yousuf and Rahman, 2007). The PWGR in Bangladesh was claimed to be 0.65 kg day^{-1} in the year 2007 (Khajuria et al., 2010), while it was projected at 0.60 kg day^{-1} in 2020, a lower PWGR projection for 13 years later (Das et al., 2014). The differences in projections made it difficult to calculate a reasonable waste generation in Bangladesh. However, there were two extensive studies, that were conducted during 2004–2005 (Alamgir and Ahsan, 2007a; Enayetullah et al., 2005). Both of the studies appeared to be consistent and reliable due to extensive surveys and were also conducted at the same time (2004–2005). From the average PWGR of these two studies, we calculated the PWGR for 2016 with adoption of the possible increase in PWGR due to economic development and escalation of living standard (Fu et al., 2015; JICA, 2005; Shekdar, 2009; Yanrong et al., 2011). Efforts were made to relate gross domestic product (GDP) growth rate and municipal solid waste generation rate for developed countries (Daskalopoulos et al., 1998) or at the global scale (Hoornweg and Bhada-Tata, 2012; Wang and Nie, 2001). Here, we adopted PWGR for 2016 using two econometric indicators, i.e., national GDP and per capita gross national income (GNI) growth rate. Because, the contribution of GDP or GNI to waste generation could vary, we propose three scenarios, i.e., low, medium, and high level of projection considering 5%, 10%, and 20% of GDP and GNI growth rate contributed to waste. However, compared to our study, a higher fraction (70%) of gross annual product growth rate is considered to calculate PWGR growth rate (Hai and Ali, 2005). Moreover, a non-linear prediction can be used, but that was not used for this study since related data were not available (Mahamah, 2009). The projected PWGR was then validated with a survey (see below).

(a) **Per capita waste generation growth rate calculation using GDP**

Per capita waste generation growth rate in each year = PWGR in a year × GDP growth rate in each year × fraction of GDP growth rate contributed to waste generation

(b) **Per capita waste generation growth rate calculation using GNI**

GNI reflects the purchasing capacity of the individuals while inflation rate (IR) reduces it. Therefore, we subtracted IR from the GNI and the waste generation growth rate was calculated as-

$$\begin{aligned} &\textit{Per capita waste generation growth rate} \\ &= \frac{(PGNIc - PGNIc \times IRc) - \{PGNIp - (PGNIp \times IRp)\}}{\{PGNIp - (PGNIp \times IRp)\}} \times 100 \\ &\quad \times \textit{fraction of GNI growth rate leaded to waste} \end{aligned}$$

where, PGNIc = Per-capita GNI in current year

IRc = Inflation rate (%) of current year

PGNIp = Percapita GNI in preceding year

IRp = Inflation rate (%) of previous year.

The PWGR was adopted using these approaches as incremental basis from the year 2005. The estimation of waste generation in metropolitan areas of Bangladesh was calculated using the World Population overview of 2016. For the projection of waste generation for 2035, the PWGR was adopted as the average growth rate of GDP and GNI between 2005 and 2016. The population of the cities in 2035 was projected considering a moderate increase of 2.5% per year although it was suggested to be 3.4% (World Bank, 2015). The reason for choosing 2.5% is that the projection trend was downwards from the year 2002 with a figure of 4.45% which decreased to 3.4% in 2015.

2.2. Survey and validation of waste generation

Waste generation data were collected through a survey of waste dumping sites in three cities, namely Dhaka, Mymensingh and Barisal, and in one municipality (Patuakhali) during May 2016. These four municipal areas were selected based on population densities and urbanization characteristics. The amount of waste at landfill sites was estimated by counting the number of trucks with their capacity used by city corporations for dumping the waste in a day (Alamgir and Ahsan, 2007a). Moreover, some key personnel of the municipal offices dealing with the waste management such as waste collectors and garbage disposal officer were also interviewed for additional data. A structured survey schedule was used for recording the data. The survey and interview based waste generation of the cities was then averaged and normalised with current population of the respective city to get PWGR, which was then used to validate the projections (details of the survey can be found in SI). In addition, we determined the pyrolysable and compostable fractions of the organic waste using a pilot survey in the four cities and municipalities mentioned above. We analysed about 200 kg of MW from five sites in four major dumping sites. First, the organic and inorganic waste were separated, while the organic waste was then classified according to the definition (Table S2b) and weighed.

2.3. Estimation of municipal solid waste composition

The constituent of MW along with definitions can be found in SI, Table S2a and b. The physical composition of MW for each city was calculated as an average from different published studies (Table S1). The waste composition of the country was calculated as a weighted average. Nevertheless, the composition of waste can vary with the change in economic development and social changes such as with technological revolution. For example, compared to 1999, a 19% increase of organic waste was projected for low-income Asian countries in 2025 while the increase was predicted to be 3% for high-income Asian countries (World Bank, 1999). However, adjustment according to this projection might be unrealistic for Bangladesh as the average organic waste is already ~70%. Based on a pilot survey, we considered that 65% of the organic waste could be compostable while the remaining 35% could be pyrolysable. Yet, the fractions can vary due to seasonal variation and state of the waste collection. For example, in summer and rainy seasons (from April to July), a higher availability of seasonal fruits may increase the size of compostable fraction while the prevailing high temperature (~30 °C), relative humidity (~80%) and rainfall (~250 mm per month) accelerate the decomposition during waste collection. The potential fuel for pyrolysis was calculated taking the sum fractions of paper, textile and wood.

2.4. Proposed waste management paradigm

The organic waste produced in metropolitan areas of Bangladesh is usually dumped to waste bins or open places in the street. Sometimes the waste is directly thrown and dumped to ditches or canals. Half of the waste is collected by municipalities and dumped in open places, as at Matuail and Amin Bazar in Dhaka (DOE, Waste Concern and ITN-BUET, 2004; Mahmud, 2014). Yet, a small portion of waste is purposefully collected for composting and biogas generation although there is no definite estimation of size of these kinds of recycling. However, it would not be more a percent. For example, few companies are commercially producing compost from MOW. A proportion of the plastic, paper and iron waste are also collected for recycling (Hoornweg and Bhada-Tata, 2012). The new techniques of waste management for Bangladesh is depicted in Fig. 2. The collected waste would be purposefully separated into different fractions, i.e., (a) compostable, (b) pyrolysable, (c) fuel for pyrolysis and (d) others constituting metals, plastic and polythene etc. Metals, plastic and polythene would be sold off and used for recycling. The fraction of compostable and pyrolysable MOW might vary depending on the decomposability and state of collection. However, on average 50% of the total waste was considered to be compostable (Table 2) while 27% could be used as pyrolysis biomass. On average the fuel, constituting paper, textile, and wood is estimated to be 10% which might increase if lignin rich biomass is included. During composting half of the waste biomass (equivalent to 25% of the initial waste biomass) might be lost as CO_2 (Tiquia et al., 2002). During pyrolysis, 35% of feedstock biomass (equivalent to ~9% of total waste) is estimated to be retained while only 10% of fuel (equivalent to ~1% of total waste) is expected to be retained as ash (Mia et al., 2015). A part of heat energy generated during pyrolysis could be used for drying of compost to a moisture content of ~50%, because a high moisture content (>70%) of compost is considered to be one of the major challenges of large-scale compost marketing. The rest heat energy could be used for drying the biomass that would be used for fuel for pyrolysis, while the rest of the heat would be used for power generation.

Like other waste management systems, the proposed system also carries some inherent challenges such as (a) separation of MOW into compostable and pyrolysable waste, (b) circulation of heat energy and (c) set-up of plants to handle large volume of waste. These challenges need to be addressed with experimentation before adoption of such technology. Although we proposed to use fuel for pyrolysis of the biomass, pyrolysis can be conducted without fuel using co-carbonization pyrolyser if external power is used to start the process. The reason of our proposition was to avoid any external power utilisation since there is limited availability of power in Bangladesh.

2.5. Estimation of nutrient recycling potentials

The recycling potential of C, N, phosphorus (P) and potassium (K) was estimated for biochar enriched composting from fresh biomass with a step-wise calculation for pyrolysis and composting (Fig. S1). This strategy was used since there are only few studies that focused on biochar blended composting with no estimation of nutrient recycling potentials (Wiedner et al., 2015). However, we considered the possible effects of co-composting on nutrients retention. In the first step, the mass of dried organic waste was calculated from fresh biomass after moisture adjustment. The moisture content of fresh organic waste varies widely depending on season, state of collection and waste composition estimating at 36–90% (BMDF, 2012; Rouf, 2011). We hypothesised a moisture content of 70% (Themelis and Kim, 2002; Uddin and Mojumder, 2011). The C content in the fresh dried organic waste was considered to be 45% although it can vary with waste composition (Das et al., 2014; Vandecasteele et al., 2016; Zhao et al., 2009). The concentration of N, P and K in fresh MOW was calculated as an average percentage from different studies (Table S6) (Alamgir and Ahsan, 2007a; BMDF, 2012; Lavangnolo, 2014; Yousuf and Rahman, 2007). The amount of net biomass return after composting was considered to be 25% (Enayetullah and Sinha, 2015). Nitrogen, P and K concentration in the compost was calculated as an average from different studies (Eghball et al., 1997; Pognani et al., 2012; Tiquia et al., 2002) while the C content was assumed to be 50% of the initial C (Hermann et al., 2011). The yield of biochar after pyrolysis is considered to be 35% (Mia et al., 2015) while C content in biochar was taken as 65%, an average from many studies (Ahmad et al., 2014; Roberts et al., 2010). To calculate N, P and K contents in biochar, an average percentage of nutrient content from different studies was used (Pituello et al., 2015; Zhao et al.,

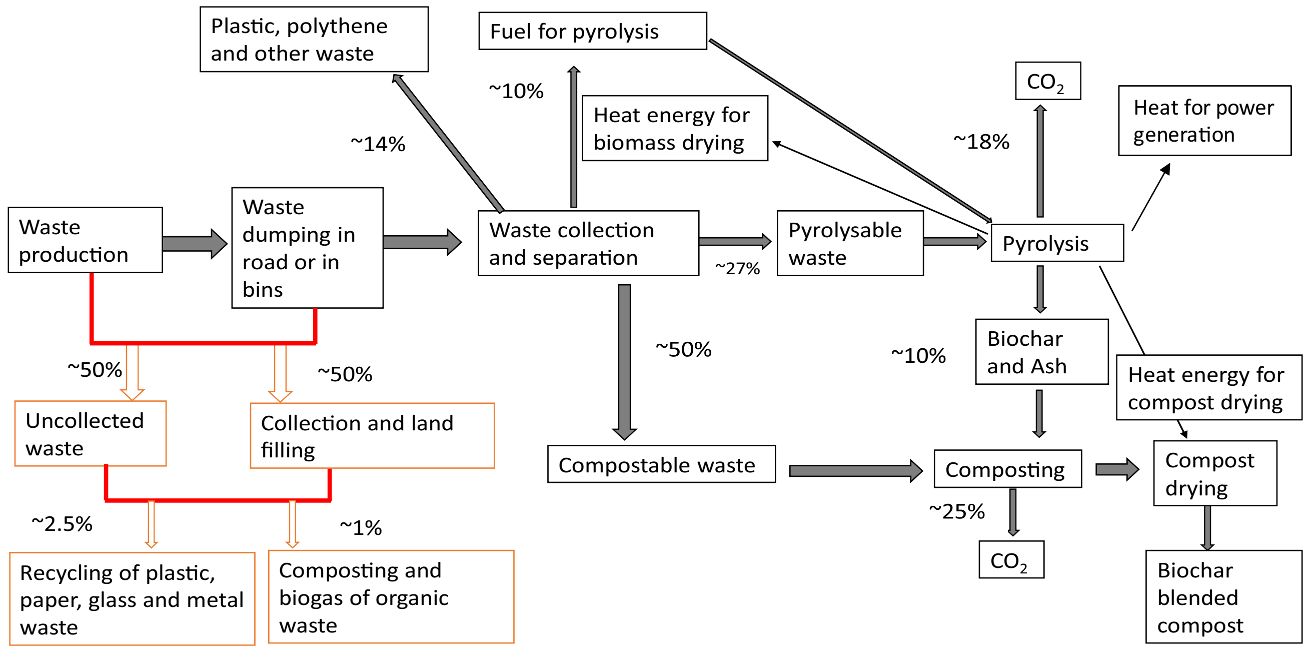

Fig. 2. New technique of waste collection and recycling (black boxes and arrows). The red arrows and boxes represent the current waste management systems. The current scenario is based on published literatures (Mahmud, 2014; Yousuf and Rahman, 2007) while the future scenario is based on calculations provided in the methodology. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2013). The yield of ash from fuel (i.e., paper, textile and wood) was considered to be 10%. The N, P and K content of ash was considered to be 0.1%, 0.79% and 2.93% (Pitman, 2006) while the C content was considered to be negligible. A conservative reduction of N loss (30%) was considered for the synergistic effect of biochar blended co-composting, although it could be as high as ~50% (Steiner et al., 2010). A 10% greater C loss from compostable organic waste and 5% from biochar were also considered for stimulative decomposition (Hamer, 2004). We only used GDP based medium projection for calculating nutrient recycling and potential economic return.

2.6. GHG emission calculation

Biochar addition in the composting biomass can reduce GHG emission with incremental effects by a higher rate of biochar addition (Sanchez-Monedero et al., 2018). For our method (19% biochar addition to composting biomass), we fitted a logarithmic model to the literature data of GHG emission reduction by co-composting (listed in the Table S8). The emission factor for the proposed method was then calculated by adopting this reduction, while emission factor for biochar technology, co-composting and GHG abatement due to landfilling was calculated using the method of Roberts et al. (2010), Friedrich and Trois, (2013) and Islam, (2017) respectively. The detailed calculation is presented in the SI (Table S9).

2.7. Return calculation

The economic return from the proposed waste management system was calculated following Zeng et al. (2005) considering a 70% recovery. This is because, 100% recovery is not always attainable in real situations. The price of the products was adopted from Alamgir and Ahsan (2007b). The price of biochar blended compost was considered as same as that of the compost, reported by several associated compost producer and retailer.

3. Results

3.1. Per capita waste generation rate

The PWGR with GDP and GNI-based three estimation levels are presented in Table 1. From the base line PWGR in 2005, the trend of its increase with different projection levels over time is presented in Fig. 3 taking Dhaka City Corporation (DCC) as an example. The year to year GDP and GNI growth rate are presented in the SI Table S3. The PWGR was greater for GNI based calculations compared to GDP based calculations and the variation was projected to increase over time. Compared to the GDP-based projection, the GNI-based projections were respectively, 1.23%, 2.5% and 4.9% greater in the low, medium and high levels of simulation in 2016 while it would be 4.9%, 9.8% and 20.2% greater in the year 2035. It is because on average the GNI growth rate was greater than GDP growth rate, i.e., 9.4% vs 6.3% (Table S3). With a medium level of projections, the simulated PWGR for 2035 would increase by 12.67% and 20.48% respectively in GDP and GNI-based estimation from the year 2016 while this increase was 7.13% and 9.76% between 2005 and 2016 (Table 1). The estimated PWGR of DCC in 2016 was at 0.541 to 0.599 and 0.547 to 0.629 kg day^{-1} respectively for GDP and GNI-based estimation. This was the highest among all cities while it was the lowest in municipalities. The PWGR of Bangladesh in 2016 was estimated at 0.308–0.341 and 0.326–0.358 kg day^{-1} respectively for GDP and GNI-based calculations. The PWGR of DCC was compared with other studies (Fig. 3). We validated our projections for 2016 with survey-based estimation in the four cities and found it to be consistent (Fig. 4), although the projections did not fit perfectly for all cities.

3.2. Municipal solid waste generation in Bangladesh

With GDP and GNI-based estimation, the waste generation of metropolitan areas of Bangladesh was estimated respectively at 15,507 and 15,888 t day^{-1} in 2016 while it was projected at 25,881 and 28,354 t day^{-1} in 2035 (Table 1). The highest waste

Table 1
Estimated waste generation for major cities and municipalities of Bangladesh in 2016 and 2035.

Name of city	Per capita waste generation ($kg\ day^{-1}$)									Population ("000")		Estimated waste generation ($t\ day^{-1}$)			
	2005[a]	GDP based low	GDP based medium	GDP based high	GNI based low	GNI based medium	GNI based high	GDP based medium projection for 2035	GNI based medium projection for 2035	2016	Projected for 2035[b]	GDP based medium growth	GNI based medium growth	GDP based medium growth for 2035	GNI based medium growth for 2035
Dhaka	0.52	0.54	0.56	0.60	0.55	0.57	0.63	0.63	0.69	10,357	16,556	5797	5939	10,442	11,440
Tungi, Gazipur	0.52	0.54	0.56	0.60	0.55	0.57	0.63	0.63	0.69	338	540	189	194	340	373
Narayanganj	0.52	0.54	0.56	0.60	0.55	0.57	0.63	0.63	0.69	224	357	125	128	225	247
Rajshahi	0.34	0.35	0.36	0.39	0.36	0.37	0.41	0.41	0.45	700	1119	254	261	458	502
Rangpur	0.25	0.26	0.27	0.29	0.26	0.27	0.30	0.30	0.33	343	549	92	94	166	181
Barisal	0.29	0.30	0.31	0.33	0.30	0.32	0.35	0.35	0.38	202	323	62	64	112	123
Chittagong	0.42	0.43	0.45	0.48	0.44	0.46	0.51	0.51	0.56	3920	6267	1764	1807	3177	3481
Khulna	0.31	0.32	0.33	0.35	0.32	0.34	0.37	0.37	0.41	1342	2146	443	454	798	874
Sylhet	0.37	0.38	0.39	0.42	0.38	0.40	0.44	0.44	0.48	237	379	93	95	167	183
Comilla	0.25	0.26	0.27	0.29	0.26	0.27	0.30	0.30	0.33	389	623	104	107	188	206
Mymensingh	0.25	0.26	0.27	0.29	0.26	0.27	0.30	0.30	0.33	225	360	60	62	109	119
Other cities	0.20	0.21	0.21	0.23	0.21	0.22	0.24	0.24	0.26	30,448	40,177	6524	6684	9699	10,626
Country average/total		0.31	0.32	0.34	0.31	0.33	0.36	0.37	0.41	48,725	69,396	15,507	15,888	25,881	28,354

[a] Data is the average of Alamgir and Ahsan (2007a) and Enayetullah et al. (2005).
[b] The projected was based on 2.5% increase of population in each year.

generation in 2016 was at DCC (5797–5939 $t\ day^{-1}$) which is ~37% of the total, followed by Chittagong City Corporation (CCC, 1764–1807 $t\ day^{-1}$) and Khulna City Corporation (KCC, ~450 $t\ day^{-1}$). The contribution of all municipalities was ~42% (6524–6684 $t\ day^{-1}$). The projected waste generation would change in 2035 with 40–44% contribution from DCC, 12–13% from CCC, 3% from KCC and 37–41% from other municipalities.

3.3. Physical composition of MW of major cities in Bangladesh

The waste composition of different cities of Bangladesh is presented in Table 2. On an average, a greater portion of the MW was organic in nature (>75%). The fraction of paper, plastic, textile and wood, metals and glass were 6.37, 3.52, 4.17, 1.18 and 2.68% of the total, respectively. The variation in physical composition of different cities was small. However, fraction of organic waste was higher in newly declared city corporations while the fraction of plastic, textile and wood were higher in the old cities, like in DCC. The fraction of compostable waste ranged between 46 and 53% with an average of 50% while the fraction of pyrolysable waste was in between 26 and 29%. The fraction of fuel ranged from 6 to 11% with an average of ~10%.

3.4. Organic waste generation in Bangladesh and its estimated different fractions

With a medium level of GDP-based estimation, the MOW generation rate was estimated at 11,884 $t\ day^{-1}$ in 2016 while it was projected at 19,750 $t\ day^{-1}$ in 2035, which suggests a 66% growth of MOW over this period (Table 3). The compostable waste was estimated to be ~7725 $t\ day^{-1}$ while the pyrolysable waste was estimated at 4151 $t\ day^{-1}$ in 2016. The potential fuel for pyrolysis was calculated at 1514 $t\ day^{-1}$ in 2016. Compost generation potential from MOW was estimated at 3862 $t\ day^{-1}$ in 2016 while it was projected at 6419 $t\ day^{-1}$ in 2035. The biochar production was estimated at 437 and 726 $t\ day^{-1}$ respectively in 2016 and 2035. If biochar and ash are co-composted with compostable waste, the biochar blended compost generation rate would respectively be at 3936 and 6543 $t\ day^{-1}$ in 2016 and 2035.

3.5. Carbon and nutrient recycling in the new paradigm

The amount of C and nutrients, specifically N, P and K that can be recycled in the new techniques from the urban areas in Bangladesh is presented in Fig. 5. This projection was made considering GDP based medium projection. The potential of C recycling was estimated at ~740 $t\ day^{-1}$ which is about half of the fresh biomass C. The pyrogenic C recycling was estimated at 272 $t\ day^{-1}$ which is ~37% of the total C that would retain through biochar blended composting. The N, P and K recovery were estimated at 34, 13 and 39 $t\ day^{-1}$ suggesting respectively a 54%, 54% and 61% recovery of the original nutrient content in the biomass.

3.6. GHG emission

The proposed method with 19% biochar addition (dry basis) to composting biomass could reduce 25.06% CO_2, 75.69% CH_4, 38.52% N_2O and 40.95% NH_3 emission in comparison to composting alone (Figs. 6 and S2). The total emission factor for each tonne of MW processing using the proposed method was calculated to be negative by −503 CO_2 e t^{-1} fresh MW, while the biogenic C loss was estimated to be 506 CO_2 e t^{-1} fresh MW (Table 4).

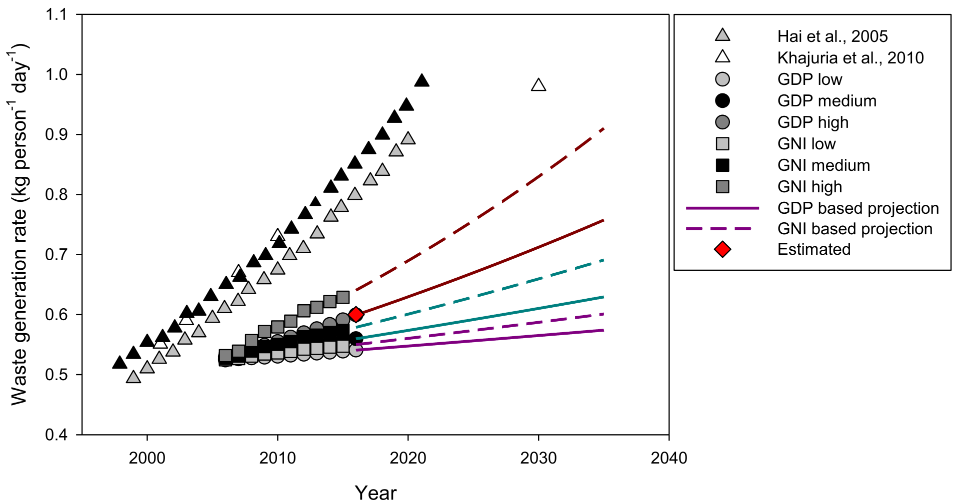

Fig. 3. Trend of estimated per capita waste generation rate (kg day^{-1}) of DCC over the years. The high, medium and low level of projections were made considering 5, 10 and 20% of national GDP growth rate leaded to waste generation. The GDP and GNI data was used from Wold Bank, 2016. The per capita waste generation projection for DCC was also included from published literature (Hai and Ali, 2005). The projection of waste generation rate of Bangladesh was adopted from Khajuria et al. (2010).

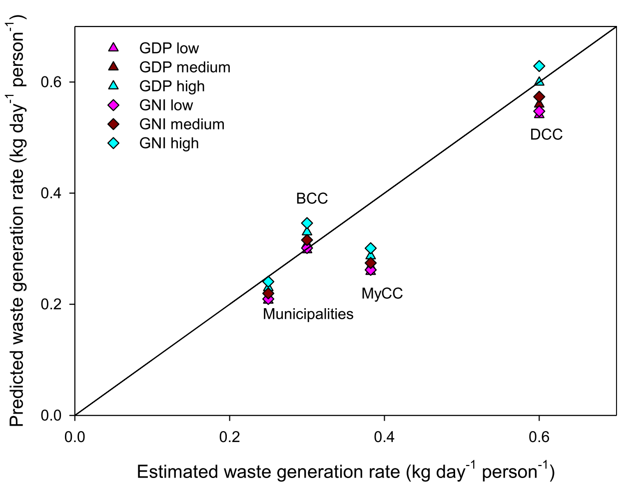

Fig. 4. Validation of estimated and projected per capita waste generation rate of selected cities in Bangladesh. DCC = Dhaka City Corporation, BCC = Barisal City Corporation, MyCC = Mymensingh City Corporation, Municipalities = PSTU campus and Dumki Upazila.

3.7. Potential returns

The estimated waste generation with medium projection i.e., 10% of GDP growth rate in the selected major cities of Bangladesh was 5660,150 t in 2016 (15,507 t day^{-1} in Table 1). Considering a 70% recovery, the revenue generation from biochar blended compost was estimated respectively at US$ 161 and 268 million in 2016 and 2035 while the total revenue was projected at US$ 201 and 335 million (Table 5). The biochar blended composting contributed the largest fraction (~80%) to the total revenue. From a tonne of municipal waste (wet basis), a revenue of US$50.76 (a total of US$ 287,318,857 from 5,660,105 t of initial waste produced in a year) can be generated (Table 5).

4. Discussion

4.1. Waste generation in Bangladesh

The waste generation of a country may depend on many factors including population size, and PWGR. The PWGR was reported to

Table 2
Waste composition of the major cities of Bangladesh (%).[d]

Waste composition	DCC	GCC[a]	NCC[a]	RCC	RaCC	BCC	CCC	KCC	SCC	CoCC[b]	MyCC[c]	Other urban areas	Country average
Organic	73.14	73.14	73.14	78.65	82.62	80.77	71.92	79.42	73.49	80.77	82.62	80.72	76.63
Paper	5.45	5.45	5.45	4.10	3.42	6.92	8.74	9.41	8.37	6.92	3.42	6.51	6.37
Plastic	3.80	3.80	3.80	5.59	4.50	3.85	3.62	3.04	3.72	3.85	4.50	3.16	3.52
Textile and wood	5.65	5.65	5.65	2.56	2.20	1.54	3.34	0.87	2.33	1.54	2.20	1.58	3.39
Leather and rubber	0.68	0.68	0.68	0.73	0.92	0.77	1.36	0.64	0.47	0.77	0.92	1.06	0.92
Metal	0.49	0.49	0.49	1.48	0.59	1.54	3.32	1.18	0.93	1.54	0.59	1.23	1.18
Glass	2.91	2.91	2.91	1.26	1.59	0.77	2.28	0.54	0.93	0.77	1.59	2.88	2.68
Others	7.88	7.88	7.88	5.93	4.18	3.85	5.42	4.90	9.77	3.85	4.18	2.86	5.30
Total	100.12	100.12	100.12	100.00	100.01	100.00	100.00	100.00	100.00	100.00	100.01	100.00	100.00
Compostable waste	47.54	47.54	47.54	51.12	53.70	52.50	46.75	51.63	47.77	52.50	53.70	52.47	49.81
Pyrolysable waste	25.60	25.60	25.60	27.53	28.92	28.27	25.17	27.80	25.72	28.27	28.92	28.25	26.82
Fuel for pyrolysis	11.10	11.10	11.10	6.66	5.62	8.46	12.08	10.28	10.70	8.46	5.62	8.09	9.76

DCC = Dhaka City Corporation, GCC = Gazipur City Corporation, NCC = Narayanganj City Corporation, RCC = Rajshahi City Corporation, RaCC = Rangpur City Corporation, BCC = Barisal City Corporation, CCC = Chittagong City Corporation, KCC = Khulna City Corporation, SCC = Sylhet City Corporation, CoCC = Comilla City Corporation, MyCC = Mymensingh City Corporation.
[a] Indicates data were used from DCC.
[b] Indicates data were used from BCC.
[c] Indicates data were used from RaCC.
[d] Data were used from Ahmed and Rahman (2000), Ahmmad and Haque (2014), Alam and Bole (2001), Alamgir and Ahsan (2007a), BMDF (2012), Chowdhury et al. (2014), Das et al. (2014), Halder et al. (2014), Hossain et al. (2014), Islam et al. (2015), JICA (2005), Khan (1999, unpublished), Lavangnolo (2014), Rahman et al. (2013), Rouf (2011), Sujauddin (2008), Uddin and Mojumder (2011), Yousuf and Rahman (2007), Zakir Hossain et al. (2014).

Table 3
Estimated organic waste with its fractions and products (fresh weight basis).

Year	Organic waste (t day^{-1})	Compostable waste (t day^{-1})	Pyrolysable waste (t day^{-1})	Pyrolysing fuel (t day^{-1})	Compost (t day^{-1})	Biochar (t day^{-1})	Biochar blended compost (t day^{-1})
2016	11,884	7725	4159	1514	3862	437	3936
2035	19,750	12,83	6912	2561	6419	726	6543

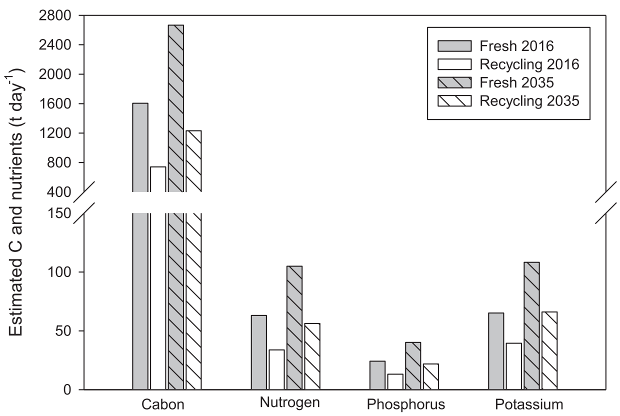

Fig. 5. Estimated C and nutrient recycling potentials from MOW in Bangladesh in 2016 and 2035 with the proposed paradigm.

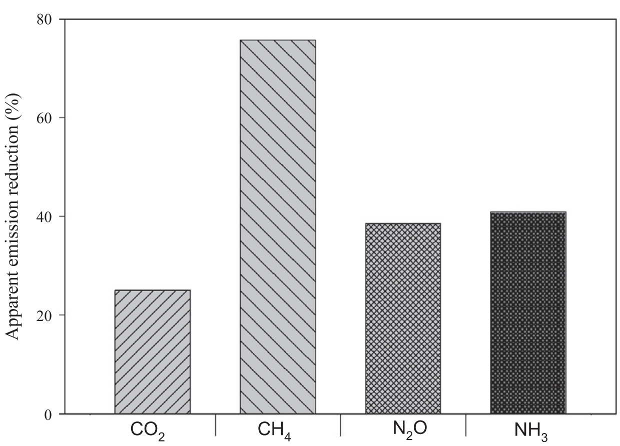

Fig. 6. Apparent reduction of CO_2, CH_4, N_2O and NH_3 emission in the proposed method compared to composting.

Table 4
Estimated emission factor for biochar blended composting.

Emission factor calculation	Positive feedback (CO_2 e)	Negative feedback (CO_2 e)	Biogenic C loss (CO_2 e)
A. Waste collection	5.70		
B. Waste sorting and processing	27.00		
C. Biochar production	6.09	71.21	48.51
D. Co-composting	22.85	143.02	457.56
E. Emission abatement for other recycled materials			
i. Plastic	17.50	51.80	
ii. Leather and rubber	3.32	6.43	
iii. Metals	5.79	52.76	
iv. Glass	13.33	7.59	
v. Others		5.30	
F. Emission abatement for exclusion of landfilling		266.92	
Overall balance	101.58	605.04	506.07

increase with economic development and upgradation of living standard (Fu et al., 2015; Shekdar, 2009; Yanrong et al., 2011). Our estimated and projected PWGR of Bangladesh was 0.31–0.36 kg day^{-1}, which is much lower than the projection of others (Hai and Ali, 2005). For example, the PWGR of Bangladesh was estimated to be 0.60 kg person^{-1} day^{-1} in 2025 (DOE, Waste Concern and ITN-BUET, 2004) while it was estimated at 0.73 kg person^{-1} day^{-1} in 2010 (Khajuria et al., 2010). This is primarily because, the initial estimation and rate of increase were lower in our estimates compared to these published studies. World Bank projected PWGR at 0.75 in 2025, which is also higher than our estimate (Hoornweg and Bhada-Tata, 2012). However, our estimated PWGR of Bangladesh was comparable to India (0.37 kg day^{-1}) and Nepal (0.32 kg day^{-1}) while lower than other south Asian countries (Kawai and Tasaki, 2016). One of the possible reasons of the large inconsistency in the projection is averaging waste generation rate. We calculated our national PWGR considering weighted average, i.e., a figure obtained by dividing the total waste generation by the total population. However, we had relatively large waste generation rate for the large cities, for example 0.52–0.63 kg day^{-1} in Dhaka. Moreover, our estimated PWGR were in reasonably good agreement with the survey-based estimation although there was not a perfect fit (Fig. 4). The discrepancies between the projection and estimation are plausible, because, the national GDP and GNI were not equally distributed. Therefore, a measurement-based estimation might be preferred to a GDP or GNI-based projection.

The daily waste generation in cities and municipalities of Bangladesh in 2016 was estimated between 15,507 and 15,888 t while it was estimated at ~13,332 t day^{-1} for the year 2005 (Enayetullah et al., 2005) and 47,064 t day^{-1} for 2025 considering the PWGR of 0.6 kg day^{-1} (DOE, Waste Concern and ITN-BUET, 2004). Compared to our estimation, this projection is much greater. Probably, a projection of PWGR at 0.6 kg day^{-1} is an over estimation, and the weighted average rather than the simple average of different cities needs to be considered. We believe that our calculations are quite robust since it took into account all municipalities where the PWGR is relatively low.

4.2. Physical composition of MW in Bangladesh

Physical composition of MW may vary depending on many factors including the nature and scale of industrialization, nature of human food habit and life style. In Bangladesh majority of waste (~75%) was organic in nature (which is basically the bio-waste and does not include paper, tyre, plastic, etc.). It was lower than Nepal (80%) and higher than India (35%) reaching similar to many other developing countries including Algeria (70%), Cuba (69%), Ethiopia (88%) and Sri Lanka (76%) (Hoornweg and Bhada-Tata, 2012). However, there was variability in waste composition in different cities of Bangladesh although the fraction of organic waste did not differ largely (ranged 73–83%). This is because, people in Bangladesh mostly use home-made food compared to other countries where a significant processed food is consumed. The share of plastic or packaging was higher in the large cities, which is consistent with the report of World Bank that projected an increase of packing waste with socio-economic development (Hoornweg and Bhada-Tata, 2012; World Bank, 1999).

Table 5
Estimated return for the proposed system.

Recyclable items	Recoverable mass ($t\ yr^{-1}$)		Price (US$ t^{-1})	Market price (US$)	
	2016	2035		2016	2035
Biochar-blended compost	1,005,740	1,671,794	160	160,918,398	267,487,063
Plastic	139,622	233,023	120	16,754,650	27,962,805
Leather and rubber	36,404	60,756	110	4,004,394	6,683,165
Metal	46,565	77,715	200	9,313,030	15,543,054
Glass	106,329	177,459	36	3,827,855	6,388,529
Others	210,162	350,752	30	6,304,872	10,522,566
Total	2,206,889	3,673,572		201,123,200	334,587,183

4.3. Nutrient recycling and returns from the proposed method

Recycling of nutrients from organic waste while harvesting of energy has always been a target for sustainable waste management. Our proposed method could recycle about half of the C, N, P and K of the organic waste (Fig. 5). The nutrient recycling, particularly N by this method, is proposed to be higher than composting alone as mineral N (both NH_4^+ and NO_3^- N) released during composting process adsorbed onto fresh biochar and protecting them from leaching and gaseous losses (see below) (Kammann et al., 2015; Mizuta et al., 2004). Similar synergistic benefits of co-composting have been reported in the literature (Steiner et al., 2010). Since C and nutrient content may vary with waste types, the recovery may change with different types of organic waste. For example, the C content in biochar can be high for woody biomass while it would be low for mineral rich biomass (Ahmed et al., 2014). Therefore, our estimates carry some uncertainties. The economic return from this method is around US$ 50.76 t^{-1} of MW. The revenue generation can vary between countries and therefore difficult to compare. For example, Fehr and Arantes (2015) proposed a return of BRL 390 t^{-1} biodegradable waste (equivalent to US$ 120).

4.4. GHG emission

While landfilling and composting emit a significant amount of GHG, our proposed method would be able to reduce 76% and 39% of CH_4 and N_2O emissions (compared to composting), respectively. This reduction is apparent meaning that CH_4 and N_2O would have been produced but could have entrapped on biochar surfaces while it is not known what would be the fate of these adsorbed gases (Hamer, 2004; Sánchez et al., 2015; Sanchez-Monedero et al., 2018). Overall, the emission factor of our method would be negative with −503 CO_2 e t^{-1} fresh MW. In terms of C footprint, our method is better than other proposed methods of waste management in Bangladesh, i.e., combined approaches of landfill gas recovery, waste to energy and material recovery facility (Islam, 2017). Moreover, the biogenic emission of CO_2 would be shrunken since biochar is recalcitrant with a higher mean residence time while the stabilisation of soil organic matter with biochar (i.e., negative priming) could further increase CO_2 emission abatement (Mia et al., 2017b; Roberts et al., 2010). Although we did not include C footprint abatement due to pollution-related disease reduction, we believe it would have significant implications and therefore, further study is needed to quantify such effects.

5. Agricultural and environmental implications

The proposed method of recycling oriented waste management could have significant implications for agriculture and environment. For example, maintenance of soil organic matter is often a challenge in many tropical countries including Bangladesh where intensive agriculture is in practice (Mia et al., 2014). The biochar blended compost contains a unique combination of labile and pyrogenic C enriched with nutrients. Application of biochar blended compost could increase soil C content and sequester a part of this C particularly the pyrogenic C (~37% of the total C) in the soil for a long time. Additionally, humified organic matter and surface activated biochar can significantly improve nutrient recycling and productivity in agricultural systems (Kammann et al., 2015; Mia et al., 2017a, 2017b). Half of the N, P and K can be recycled, which otherwise would have been a missed opportunity. Recycling of organic waste would benefit river ecosystems around cities that are extremely burdened with decomposing organic waste aggravating eutrophication and death of aquatic flora and fauna. Moreover, landfilling and blocking of drainage and sewerage channels could be reduced significantly. Additionally, the overall GHG emission abatement would enhance mitigating climate change. Thus, the method can result in win-win situations. Provided technological complexities and unprecedented risk of heavy metal contaminations, we need to carefully examine the systems before any largescale investment and soil application.

6. Future research

The new approach requires further laboratory and field research in several aspects before its large-scale adoption. Examining changes in microbial community during co-composting would provides additional information for its role as soil amendment. A comprehensive life cycle assessment of this approach would provide economic relevance of this technology.

7. Conclusions

Estimation of waste generation is a challenge for Bangladesh while our econometric model based waste estimation provide a good prediction of PWGR. Our proposed model of waste management could recycle ~50% of C, N, P and K to agricultural systems. The new techniques could generate economic return estimating at US $ 210 million in Bangladesh in the 2016 while provide a benefit of −503 CO_2 t^{-1} fresh MW emission abatement. This self-sustaining waste management system can improve the environmental quality and provide benefits to agriculture. However, success of such waste management approach will largely depend on how it will be combined with present waste management systems.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.wasman.2018.01.038.

References

Agyarko-Mintah, E., Cowie, A., Singh, B.P., Joseph, S., Van Zwieten, L., Cowie, A., Harden, S., Smillie, R., 2017a. Biochar increases nitrogen retention and lowers greenhouse gas emissions when added to composting poultry litter. Waste Manage. 61, 138–149.

Ahmad, M., Rajapaksha, A.U., Lim, J.E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S.S., Ok, Y.S., 2014. Biochar as a sorbent for contaminant management in soil and water: A review. Chemosphere. 99, 19–33.

Ahmed, M.F., Rahman, M.M., 2000. Water Supply and Saniation:rural and Low Income Urban Communities. ITN-Bangladesh, Dhaka.

Ahmmad, M.R., Haque, S., 2014. Providing electricity by digester types on biogas productions from municipal solid waste in Dhaka city, Bangladesh. Int. J. u- e-Serv. Sci. Technol. 7, 103–112.

Alam, M.J., Bole, B., 2001. Energy recovery from municipal solid waste in Dhaka city. In: Proceddings of the International Conference on Mechanical Engineering. Dhaka, pp. 125–130.

Alamgir, M., Ahsan, A., 2007a. Municipal solid waste and recovery potential: Bangladesh perspective. Iran. J. Environ. Heal. Sci. Eng. 4, 67–76.

Alamgir, M., Ahsan, A., 2007b. Characterization of MSW and nutrient contents of organic component in Bangladesh. Electron. J. Environ. Agric. Food Chem. 6, 1945–1956.

BMDF, 2012. Study on municipal solid waste management. Dhaka, Bangladesh. http://www.bmdf-bd.org/Publication (Accessed on 16.12.20).

Cáceres, R., Janczak, D., Dach, J., Czekała, W., Malin, K., 2016. Co-composting of poultry manure mixtures amended with biochar – the effect of biochar on temperature and C-CO_2 emission. Bioresour. Technol. 200, 921–927.

Chen, W., Liao, X., Wu, Y., Liang, J.B., Mi, J., Huang, J., Zhang, H., Wu, Y., Qiao, Z., Li, X., Wang, Y., 2017. Effects of different types of biochar on methane and ammonia mitigation during layer manure composting. Waste Manage. 61, 506–515.

Chowdhury, A.H., Mohammad, N., Haque, R.U., Hossain, T., 2014. Developing 3Rs (reduce, reuse and recycle) strategy for waste management in the urban areas of Bangladesh: socioeconomic and climate adoption mitigation option. IOSR. J. Environ. Sci. Toxicol. Food Technol. 8, 9–18.

Das, B.K., Kader, A., Hoque, S.M.N., 2014. Energy recovery potential from municipal solid waste in Rajshahi city by landfill technique. Int. J. Renew. Energy Res. 4, 349–354.

Daskalopoulos, E., Badr, O., Probert, S.D., 1998. Municipal solid waste: a prediction methodology for the generation rate and composition in the European Union countries and the United States of America. Resour. Conserv. Recycl. 24, 155–166.

Dias, B.O., Silva, C.A., Higashikawa, F.S., Roig, A., Sánchez-Monedero, M.A., 2010. Use of biochar as bulking agent for the composting of poultry manure: effect on organic matter degradation and humification. Bioresour. Technol. 101, 1239–1246.

DOE, Waste Concern, ITN-BUET, 2004. SAARC workshop on solid waste management, country paper-Bangladesh. Dhaka, Bangladesh.

Eghball, B., Power, J.F., Gilley, J.E., Doran, J.W., 1997. Nutrient, carbon, and mass loss during composting of beef cattle feedlot manure. J. Environ. Qual. 26, 189.

Enayetullah, I., Sinha, A.H.M., 2015. Opportunity of co-benefits of climate change mitigation actions from waste:experience of waste concern in Bangladesh. In: Climate Change in Bangladesh. Dhaka, Bangladesh, pp. 1–22.

Enayetullah, I., Sinha, A.H.M.M., Khan, S.S.A., 2005. Urban Solid Waste Management Scenario of Bangladesh: Problem and Prospects. Waste Concern Technical Document, Dhaka, Bangladesh.

Fehr, M., Arantes, C.A., 2015. Making a case for recyling biodegradable municipal waste. Environ. Syst. Decis. 35. 783 489.

Fischer, D., Glaser, B., 2012. Synergisms between compost and biochar for sustainable soil amelioration. In: Sunil, K., Bharti, A. (Eds.), Management of Organic Waste. InTech, Rijeka, Croatia, pp. 167–198.

Friedrich, E., Trois, C., 2013. GHG emission factors developed for the recycling and composting of municipal waste in South African municipalities. Waste Manage. 33, 2520–2531.

Fu, H., Li, Z., Wang, R., 2015. Estimating municipal solid waste generation by different activities and various resident groups in five provinces of China. Waste Manage. 41, 3–11.

Giusti, L., 2009. A review of waste management practices and their impact on human health. Waste Manage. 29, 2227–2239.

Hai, F., Ali, M., 2005. A study on solid waste management system of Dhaka city corporation: effect of composting and landfill location. UAP J. Civ. Environ. Eng. 1, 18–26.

Halder, P.K., Paul, N., Beg, M.R.a, 2014. Assessment of biomass energy resources and related technologies practice in Bangladesh. Renew. Sustain. Energy Rev. 39, 444–460.

Hamer, U., 2004. Interactive priming of black carbon and glucose mineralisation. Org. Geochem. 35, 823–830.

Hermann, B.G., Debeer, L., De Wilde, B., Blok, K., Patel, M.K., 2011. To compost or not to compost: carbon and energy footprints of biodegradable materials' waste treatment. Polym. Degrad. Stab. 96, 1159–1171.

Hijikata, N., Yamauchi, N., Ishiguro, M., Ushijima, K., Funamizu, N., 2015. Suitability of biochar as a matrix for improving the performance of composting toilets. Waste Manage. Res. 33 (4), 313–321.

Hoornweg, D., Bhada-Tata, P., 2012. What a waste-a global review of solid waste management. World Bank Urban Development Knowledge Paper, Washington D.C.

Hossain, L., Das, S.R., Talukder, S., Hossain, M.K., 2014. Generation of municipal solid waste in commercial city of Bangladesh. J. Environ. Treat. Tech. 2, 109–114.

Islam, K.M.N., 2017. Greenhouse gas footprint and the carbon flow associated with different solid waste management strategy for urban metabolism in Bangladesh. Sci. Total Environ. 580, 755–769.

Islam, M.S., Sultana, A., Rasheduzzaman, M., Kundu, G.K., Kamal, A.K.I., Uddin, M.K., 2015. Assessment of the present state and economical prospects of solid waste at Amin Bazar Waste Dumping Site, Dhaka, Bangladesh. J. Sci. Res. 7, 129–137.

JICA, 2005. The study on the solid waste management in Dhaka city-clean Dhaka master plan. Dhaka, Bangladesh.

Jindo, K., Suto, K., Matsumoto, K., García, C., Sonoki, T., Sanchez-Monedero, M.A., 2012. Chemical and biochemical characterisation of biochar-blended composts prepared from poultry manure. Bioresour. Technol. 110, 396–404.

Joseph, S., Graber, E.R., Chia, C., Munroe, P., Donne, S., Thomas, T., Nielsen, S., Marjo, C., Rutlidge, H., Pan, G.X., Li, L., Taylor, P., Rawal, A., Hook, J., 2013. Shifting paradigms: development of high-efficiency biochar fertilizers based on nano-structures and soluble components. Carbon Manage. 4 (3), 323–343.

Kammann, C.I., Schmidt, H., Messerschmidt, N., Linsel, S., Steffens, D., Müller, C., Koyro, H., Conte, P., Stephen, J., 2015. Plant growth improvement mediated by nitrate capture in co-composted biochar. Sci. Rep. 5, 11080.

Kawai, K., Tasaki, T., 2016. Revisiting estimates of the municipal solid waste generation per capita and their reliability. J. Mater. Cycles Waste Manage. 18, 1–13.

Karn, S.K., Harada, H., 2001. Surface water pollution in three urban territories of Nepal, India, and Bangladesh. Environ. Manage. 28, 483–496.

Khajuria, A., Yamamoto, Y., Morioka, T., 2010. Estimation of municipal solid waste generation and landfill area in Asian developing countries. J. Environ. Biol. 31, 649–654.

Khan, M.M.H., 1999. Use of kitchen waste as animal feed (Unpublished B.Sc. A.H. Report). Bangladesh Agricultural University, Mymensingh, Bangladesh.

Khan, N., Clark, I., Sánchez-Monedero, M.A., Shea, S., Meier, S., Bolan, N., 2014. Maturity indices in co-composting of chicken manure and sawdust with biochar. Bioresour. Technol. 168, 245–251.

Lavangnolo, C., 2014. A glance at the world. Waste Manage. 34, 1092–1095.

LeCroy, C., Masiello, C.A., Rudgers, J.A., Hockaday, W.C., Silberg, J.J., 2013. Nitrogen, biochar, and mycorrhizae: alteration of the symbiosis and oxidation of the char surface. Soil Biol. Biochem. 58, 248–254.

Li, R., Wang, Q., Zhang, Z., Zhang, G., Li, Z., Zheng, J., 2015. Nutrient transformation during aerobic composting of pig manure with biochar prepared at different temperatures. Environ. Technol. 36, 815–826.

Mahamah, D.S., 2009. Socioeconomic models of solid waste generation in an industrializing region. J. Solid Waste Technol. Manage. 35, 258–269.

Mahmud, A.H., 2014. City waste management: only 51% collected for disposal. Dhaka Trib. 5.

Mahmud, K., Hossain, M.D., Shams, S., 2012. Different treatment strategies for highly polluted landfill leachate in developing countries. Waste Manage. 32, 2096–2105.

Mia, S., Abuyusuf, M., Sattar, M.A., Islam, A., Hiemstra, T., Jeffery, S., 2014. Biochar amendment for high nitrogen and phosphorous bio-availability and its potentiality of use in Bangladesh agriculture: a review. J. Patuakhali Sci. Technol. Univ. 5, 145–156.

Mia, S., Dijkstra, F.A., Singh, B., 2017a. Long-term aging of biochar: a molecular understanding with agricultural and environmental implications. Adv. Agron. 141, 1–51.

Mia, S., Singh, B., Dijkstra, F.A., 2017b. Aged biochar affects gross nitrogen mineralisation and recovery: a ^{15}N study in two contrasting soils. GCB Bioenergy in press.

Mia, S., Uddin, N., Hossain, S.A.A.M., Amin, R., Mete, F.Z., Hiemstra, T., 2015. Production of biochar for soil application: a comparative study of three kiln models. Pedosphere 25, 696–702.

Mizuta, K., Matsumoto, T., Hatate, Y., Nishihara, K., N.T, 2004. Removal of nitrate-nitrogen from drinking water using bamboo powder charcoal. Bioresour. Technol. 95, 225–257.

Pitman, R.M., 2006. Wood ash use in forestry – a review of the environmental impacts. Forestry 79, 563–588.

Pituello, C., Francioso, O., Simonetti, G., Pisi, A., Torreggiani, A., Berti, A., 2015. Characterization of chemical – physical, structural and morphological properties of biochars from biowastes produced at different temperatures. J. Soils Sediments 15, 792–804.

Pognani, M., Barrena, R., Font, X., Sánchez, A., 2012. A complete mass balance of a complex combined anaerobic/aerobic municipal source-separated waste treatment plant. Waste Manage. 32, 799–805.

Rafizul, I.M., Alamgir, M., 2012. Characterization and tropical seasonal variation of leachate: results from landfill lysimeter studied. Waste Manage. 32, 2080–2095.

Rahman, A., Hossain, L., Rubaiyat, A., Mamun, S.A., Khan, Z.A., Sayem, M., Hossain, M. K., 2013. Solid waste generaiton, characteristics and disposal at Chittagong University Campus, Chittagong, Bangladesh. Discov. Sci. 4, 25–30.

Roberts, K.G., Gloy, B.A., Joseph, S., Scott, N.R., Lehmann, J., 2010. Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. Environ. Sci. Technol. 44, 827–833.
Rouf, M.A., 2011. Prospect of electric energy from solid wastes of Rajshahi city corporation: a metropolitan city in Bangladesh. In: 2nd International Conference on Environmental Engineering and Applications, pp. 43–51.
Sánchez-García, M., Alburquerque, J.A., Roig, A., Cayuela, M.L., 2015. Biochar accelerates organic matter degradation and enhances N mineralisation during composting of poultry manure without a relevant impact on gas emissions. Bioresour Technol. 192, 272–279.
Sanchez-Monedero, M.A., Cayuela, M.L., Roig, A., Jindo, K., Mondini, C., Bolan, N., 2018. Role of biochar as an additive in organic waste composting. Bioresour. Technol. 247, 1155–1164.
Sánchez, A., Artola, A., Font, X., Gea, T., Barrena, R., Gabriel, D., Sánchez-Monedero, M.Á., Roig, A., Cayuela, M.L., Mondini, C., 2015. Greenhouse gas emissions from organic waste composting. Environ. Chem. Lett. 13, 223–238.
Shekdar, A.V., 2009. Sustainable solid waste management: an integrated approach for Asian countries. Waste Manage. 29, 1438–1448.
Singh, R.P., Tyagi, V.V., Allen, T., Ibrahim, M.H., Kothari, R., 2011. An overview for exploring the possibilities of energy generation from municipal solid waste (MSW) in Indian scenario. Renew. Sustain. Energy Rev. 15, 4797–4808.
Steiner, C., Das, K.C.C., Melear, N., Lakly, D., 2010. Reducing nitrogen loss during poultry litter composting using biochar. J. Environ. Qual. 39, 1236–1242.
Sujauddin, M., 2008. Household solid waste characteristics and management in Chittagong, Bangladesh. Waste Manage. 28, 1688–1695.
Sun, D., Lan, Y., Xu, E.G., Meng, J., Chen, W., 2016. Biochar as a novel niche for culturing microbial communities in composting. Waste Manage. 54, 93–100.
Themelis, N.J., Kim, Y.H., 2002. Material and energy balances in a large-scale aerobic bioconversion cell. Waste Manage. Res. 20, 234–242.
Tiquia, S.M., Richard, T.L., Honeyman, M.S., 2002. Carbon, nutrient, and mass loss during composting. Nutr. Cycl. Agroecosys. 62, 15–24.
Uddin, M., Mojumder, S.S., 2011. Biogas Production From Municipal Waste : Prospect in Bangladesh. Interdiscip. J. Sci. Technol. October Ed, 1–5.
World Resources Institute (WRI), 2014. Country greenhouse gas emissions data-Bangladesh. Accessed on 15 January, 2018 at http://www.wri.org/resources/data-sets/cait-country-greenhouse-gas-emissions-data.
Vandecasteele, B., Sinicco, T., D'Hose, T., Vanden Nest, T., Mondini, C., 2016. Biochar amendment before or after composting affects compost quality and N losses, but not P plant uptake. J. Environ. Manage. 168, 200–209.
Wang, H., Nie, Y., 2001. Municipal solid waste characteristics and management in China. J. Air Waste Manage. Assoc. 51, 250–263.
Wiedner, K., Fischer, D., Walther, S., Criscuoli, I., Favilli, F., Nelle, O., Glaser, B., 2015. Acceleration of biochar surface oxidation during composting? J. Agric. Food Chem. 63, 3830–3837.
World Bank, 1999. What a waste: solid waste management in Asia. Washington D.C.
World population overview. http://worldpopulationreview.com/countries/bangladesh-population/cities/ (Accessed 16.12.20).
World Bank, 2015. http://data.worldbank.org/indicator/SP.URB.GROW (Accessed 17.04.05).
Wu, H., Lai, C., Zeng, G., Liang, J., Chen, J., Xu, J., Dai, J., Li, X., Liu, J., Chen, M., Lu, L., Hu, L., Wan, J., 2016. The interactions of composting and biochar and their implications for soil amendment and pollution remediation: a review. Crit. Rev. Biotechnol. 37, 754–764.
Yanrong, W., Cuili, W., Han, W., 2011. Research on the quantitative relationship between the generation of industrial solid waste and per capita GDP of Henan province. Energy Procedia 5, 593–597.
Yousuf, T. Bin, Rahman, M., 2007. Monitoring quantity and characteristics of municipal solid waste in Dhaka City. Environ. Monit. Assess. 135, 3–11.
Zakir Hossain, H.M., Hasna Hossain, Q., Uddin Monir, M.M., Ahmed, M.T., 2014. Municipal solid waste (MSW) as a source of renewable energy in Bangladesh: revisited. Renew. Sustain. Energy Rev. 39, 35–41.
Zeng, Y., Trauth, K.M., Peyton, R.L., Banerji, S.K., 2005. Characterization of solid waste disposed at Columbia Sanitary Landfill in Missouri. Waste Manage. Res. 23, 62–71.
Zhang, J., Lü, F., Luo, C., Shao, L., He, P., 2014a. Humification characterization of biochar and its potential as a composting amendment. J. Environ. Sci. 26, 390–397.
Zhang, J., Lü, F., Shao, L., He, P., 2014b. The use of biochar-amended composting to improve the humification and degradation of sewage sludge. Bioresour. Technol. 168, 252–258.
Zhang, L., Sun, X., 2014c. Changes in physical, chemical, and microbiological properties during the two-stage co-composting of green waste with spent mushroom compost and biochar. Bioresour. Technol. 171, 274–284.
Zhao, L., Cao, X., Wang, Q., Yang, F., Xu, S., 2013. Mineral constituents profile of biochar derived from diversified waste biomasses: implications for agricultural applications. J. Environ. Qual. 42, 545.
Zhao, W., der Voet, E., Van Zhang, Y., Huppes, G., 2009. Life cycle assessment of municipal solid waste management with regard to greenhouse gas emissions: case study of Tianjin. China. Sci. Total Environ. 407, 1517–1526.