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Renewable energy generation from livestock waste for a sustainable circular economy in Bangladesh

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ABSTRACT

In a developing country like Bangladesh, there exists research gaps on the long-term trend, regional variation, potential renewable energy use from livestock wastes in the urban areas as a means for circular economy adoption, associated climate change mitigation benefits, and policy regime analysis. This study investigates the (i) pattern and regional variation in greenhouse gas (GHG) emissions from the livestock sector, (ii) climate change mitigation benefits of circular economy-based resource consumption from livestock waste-based renewable biogas use in the urban areas of Bangladesh, and (iii) policies and measures driving the renewable energy generation from livestock wastes. This research employed standard GHG emission quantification model, and scenario analysis. Between 1996 and 2016, the GHG emissions of Bangladesh's livestock sector increased from 20.54 to 26.55 million of carbon dioxide equivalent (Mt CO_{2eq}). The business as usual (BAU) scenario exhibits 2.37 times growth from 26.55 Mt CO_{2eq} in 2016 to 62.96 Mt CO_{2eq} in 2050. In the liquefied petroleum gas (LPG) substitution scenario, GHG emissions fall to 37.56 Mt CO_{2eq} by 2050. A combination of all the renewable energy use measures can result in a drop of 37.5% GHG emissions compared to the BAU level. The study observed that promoting the biogas generation from livestock wastes through commercial biogas generation is currently absent in Bangladesh. Most of the existing financial schemes and subsidy programs are dedicated to the household level. The outcome is supportive to enhance renewable energy use in urban areas of Bangladesh and other countries alike thinking to promote the circular economy.

1. Introduction

Climate change mitigation benefits and developing a resource-efficient society utilizing the wastes from the livestock sector at regional to global scales has been investigated extensively [1–3]. To this end, the authors did not find any scholarly work focusing on (i) pattern and regional variation in greenhouse gas (GHG) emissions from the livestock sector, (ii) climate change mitigation benefits of circular economy-based resource consumption from livestock waste-based renewable biogas use in the urban areas of Bangladesh, and (iii) policies and measures driving the renewable energy generation from livestock wastes. This study argues that these aspects are crucial, and can have an influence on a contribution from Bangladesh, and hence globally for achieving the stringent mitigation goal of 1.5 °C set out in the Paris Agreement [2,4].

The potential of renewable energy utilizing livestock manure is assessed elsewhere, such as livestock waste to energy generation in the urban area [5–10]; and livestock waste to fuel for transportation in cities [11–15]. A comprehensive review of carbon, water footprints, and economic sustainability of renewable fuel production from multiple bio-feedstocks is recently conducted [16]. The assessment of the role of bioenergy for the European Union transport sector is also conducted [17]. Issues related to incentive and institutional-regulatory support for the diffusion of biogas in the European Union are also explored [18]. There exist few studies on renewable and renewable energy generation potential in Bangladesh from biomass and animal wastes [19–21]; municipal waste to energy generation in urban areas, and associated climate change mitigation benefits [22]; animal waste-based biogas digester technology [23,24]. But, these studies lack a comprehensive

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Abbreviations

CNG	Compressed natural gas
GDP	Gross domestic product
GHG	Greenhouse gas
GIZ	German Technical Cooperation
GS	Grameen Shakti
GWP	Global warming potential
IDCOL	Infrastructure Development Company
LCA	Life cycle assessment
LGED	Local Government Engineering Department
LPG	Liquefied petroleum gas
NDBMP	National Domestic Biogas and Manure Program
NDC	Nationally determined contribution
PPA	Power Purchase Agreement
PSMP	Power Sector Master Plan
SEC	Securities and Exchange Commission
SED	Sustainable Energy for Development
SNC	Second national communication
SNV	Netherlands Development Organization

assessment regarding climate change mitigation benefits of livestock wastes based energy use for transportation, cooking energy, and electricity in the urban, and suburban areas as a means of circular economy adoption, and associated policy analysis in Bangladesh.

Of the agriculture sector GHG emissions of Bangladesh, the livestock sector accounts for approximately 47%, 50%, and 55% of the emission in 1994, 2005, and 2012 [25–27]. Livestock sector emissions reduction is not included for 5% unconditional, and 15% conditional target in the nationally determined contribution (NDC). Yet, lowering the CH_4 emission from the cattle population is mentioned as possible conditional action-based climate change mitigation contributions in the NDC [28]. The country wants to ensure low carbon economic growth as the most vulnerable country to the threats of climate change. Such commitment is manifested in several strategies [28–32]. It is already reported, livestock sector emissions can be lowered by the measures like livestock waste to energy and transportation fuel for the urban areas, which can also help a country to achieve the NDC target on energy and transport sectors emissions reduction [5,8]. Yet such aspects are not explored in Bangladesh.

Renewable energy development from livestock manure through biogas plants is gradually developing in the country, which was started during the decade of the 1970s. More than 100,000 biogas plants have been installed so far across the country by different NGOs, particularly with the initiative of (i) National Domestic Biogas and Manure Program (NDBMP) under the overall coordination of Infrastructure Development Company (IDCOL),[1] (ii) German Technical Cooperation (GIZ) owned Sustainable Energy for Development (SED) Program, (iii) Netherlands Development Organization (SNV), and (iv) government agencies like Local Government Engineering Department (LGED), and Bangladesh Council of Scientific and Industrial Research (BCSIR) [23,33]. Initially, the dissemination of livestock manure-based renewable biogas energy generation was very poor. The government conducted a significant dissemination push with the 'Biogas Pilot Plant Project' in 1995 administered by the BCSIR, and constructed more than 25,000 biogas digesters (fixed dome cattle manure-based). Similarly, IDCOL through NDBMP constructed 37,269 biogas digesters from 2006 to 2012 [23,33,34]. The government organization like IDCOL with its 42-field based partner organization, and BCSIR along with NGO's like Grameen Shakti (GS), and Bangladesh Rural Advancement Committee (BRAC) are currently engaged in the dissemination of livestock manure-based biogas digesters (1.2–4.8 m^3 biogas generation capacity).

Due to a lack of proper enabling environment including technology, political and economic, the current renewable energy share in the country is 2.84% of the generated power [35]. The renewable energy target is 5% and 10% of total power generation by 2015, and 2020, respectively [36]. The country's annual renewable energy generation from solar, hydro, wind, biomass, and livestock manure is around 375, 230, 3, and 20 MW, respectively (Table 1) [35]. The most popular technology in the country is fixed dome digesters to generate renewable energy from livestock manure, with 90% feedstock from cow dung, followed by poultry waste (6%), and other substrates like crop residue (1–2%) [23,34]. More than 100,000 biogas plants have already been installed, of which around 50% under the NDBMP of IDCOL, and more than 25% under the Biogas Pilot Plant Project of BCSIR (Table 2).

Given this, our key research question is '*what is the (i) pattern and regional variation in GHG emissions from livestock sector, (ii) climate change mitigation benefits of circular economy-based resource consumption from livestock waste-based biogas use in the urban areas of Bangladesh, and (iii) policies and measures driving the renewable energy generation from livestock wastes*?' The study aimed at investigating livestock sector long-term emissions profile and regional variation along with the economic growth and urbanization affecting the emissions. The study also assessed renewable energy potential based on circular economy principles for different purposes like cooking, electricity, and transportation energy in urban areas, and associated climate change mitigation benefits. By comparing with policies and measures with other countries showing good progress on renewable energy from livestock wastes, our goal is to provide policymakers and associated stakeholder's information on diversifying urban and suburban energy mix, along with climate change mitigation benefits, particularly for renewable energy generation in urban and sub-urban areas of Bangladesh and countries alike.

2. Methods

2.1. Theoretical framework

2.1.1. Greenhouse gas emissions

The methodological approaches of IPCC (2006) guidelines were used to estimate the carbon footprint and avoidance from the livestock sector [39]. This study adopted the tier 1 enteric fermentation emission factors (see Table 10.10 and 10.11 of the IPCC 2006 guideline) [39] and based on the average body weight of the livestock species mentioned in the second national communication (SNC) [26]. This is because the emission factors good to be country-specific, and need not be restricted solely to regional characteristics [39]. CH_4 emission factors for manure management for different livestock (see Table 10.14, 10.15, 10.16 of IPCC 2006 guideline) are reported by average annual temperature (°C) [39]. Since the regional variation is not distinct, the annual mean surface air temperature in Bangladesh considered as 25.5 °C [40], and corresponding emission factors were used. IPCC Tier 1 default emission factors data (Table 10A–4 to 10A-8 of IPCC 2006 guideline) for each livestock category of the Indian subcontinent were applied [39].

Table 1
Renewable energy target, potential, and achievement in Bangladesh.

Source	Generation target for 2015 to 2020 (MW)	Achievement as in 2019 (MW)	Technical potential (MW)
Solar	200–800	375	3000–5000
Wind	200–500	3	100
Biomass and biogas	90–255	18–20 (cooking gas), 1 (biogas to electricity)	1200
Hydro	1500–2000	230	500–3500
Tidal	1–2	0	5

Sources [34–37]:.

[1] A government formed public limited company.

Table 2
Cumulative number of Biogas digester installed in Bangladesh by different organizations.

Organizations	2013	2015	2018
IDCOL	31,258	35,000	51,800
BCSIR	22,334	23,000	~25000
Grameen Shakti	7200	8000	~12000
NGOs and others	9850	11,530	~15000

Sources [23,23,33,38]:.

The study adopted a gate-to-gate life cycle assessment (LCA) approach considering the only value-added process of the entire production chain, such as the production of livestock, production of biogas, and production of electricity. Thus, the system boundaries covered enteric fermentation, manure management, biogas generation, electricity generation, and biogas-based transportation fuel use. Neither the upstream (e.g.-feed production and non-feed production like infrastructure) nor the downstream (e.g. - post farm gate like transport of live animals) systems were included. The biogas emission factor was considered null due to its biogenic character [41].

2.1.2. Renewable energy generation

The study quantified renewable energy generation through livestock manure-derived biogas for replacing: (a) natural gas for cooking; (b) liquefied petroleum gas (LPG) for cooking; (c) fossil fuel-based electricity substation in the residential sector; and (d) compressed natural gas (CNG) fuel substitution. Biogas potential of this study was analyzed considering small ruminants (sheep and goats), large ruminants (buffaloes and cattle), and poultry. Daily manure generation varies depending on animal age, type, and weight [5,8,42]. Manure generation varies from 10 to 20 kg/day for cattle (5–9% of body weight), 2 kg/day for sheep and goat (4–5% of body weight), and 0.08–0.1 kg/day for chicken (3–4% of body weight) [42–44]. However, manure generation quantity considered in this study were, 9% of the body weight/day, 4% of the body weight/day, and 3% of the body weight/day [42,45]; and average body weight accounted were 190 kg (large ruminants), 20 kg (small ruminants) and 1.5 kg (poultry) [26]. So, the estimated manure per day was 17 kg (large ruminants), 0.8 kg (small ruminants), and 0.045 kg (poultry).

2.2. Analytical framework

2.2.1. Greenhouse gas emissions

The study estimated enteric fermentation CH_4 emissions using Equation (1) [39].

$$M_{LE} = \sum_{(x)} \frac{(EEFx \times Nx)}{10^6} \tag{1}$$

Here, M_{LE} represents the CH_4 emissions from enteric fermentation in Gg CH_4 yr^{-1}. Based on IPCC fifth assessment (AR5) report, the global warming potential (GWP) value of CH_4 [34] for a 100-year time horizon was used to express the result in CO_{2eq} [46]. 1 Gg = 1000 tonnes conversion factor was used to expresses the result in tonnes CO_{2eq}. E_EF_x represents the emission factor for enteric fermentation of livestock in kg CH_4 $head^{-1}$ yr^{-1}. N_x represents the number of head of livestock, whereas x represents the livestock category.

Equation (2) was used to calculate the CH_4 emissions from manure [39].

$$M_{LMM} = \sum_{(x)} \frac{(EMMFx \times Nx)}{10^6} \tag{2}$$

Here, M_{LMM} represents the CH_4 emissions from manure management in Gg CH_4 yr^{-1}. Similar GWP and conversation factor mentioned in section 2.2.1 was used to expresses the result in tonnes CO_{2eq}. $E_{MM}F_x$ represents emission factor for manure management in kg CH_4 $head^{-1}$ yr^{-1}.

Equation (3) was used to calculate the direct N_2O emissions from manure management [39].

$$N_{DMM} = \left[\sum_s \left[\sum_x (Nx \times NEXx \times MSxs) \right] \times EFs \right] \times \frac{44}{28} \tag{3}$$

Here, N_{DMM} represents direct N_2O emissions from manure management in the country in kg N_2O yr^{-1}. N_x represents the number of livestock per category with x as a category of livestock. NEX_x represents annual mean N excretion in kg N $animal^{-1}$ yr^{-1}. MS_{xs} represents the fraction of total annual nitrogen excretion for each livestock category, managed under specific manure management system representing as S. EF_s represents emission factor for direct N_2O emissions from specific manure management system S in kg N_2O–N/kg N. 44/28 is a conversion factor for the conversion to N_2O. GWP value of N_20 (298) for a 100-year time horizon was used to express the result in CO_{2eq} [46]. 1000 Kg = 1-tonne conversion factor was used to expresses the result in tonnes CO_{2eq}.

Equations (4) and (5) were used to account for the indirect N_2O emissions from manure management [39].

$$N_{VMM} = \left[\sum_s \left[\sum_x (Nx \times NEXx \times MSxs \right) \times \left(\frac{FracGasMs}{100} \right) xs \right] \times EF \right] \times \frac{44}{28} \tag{4}$$

Here, N_{VMM} represents indirect N_2O emissions from the volatilization of the manure from the manure management system in kg N_2O yr^{-1}. $Frac_{GasMs}$ represents the managed manure nitrogen percentage that volatilizes as NH_3 and NOx (See Table 10.22 of the IPCC 2006 guideline). EF represents N_2O emission factor from volatilization with the default of 0.01 kg N_2O–N (See Table 11.3 of IPCC 2006 guideline) [39]. Other elements of the equation symbolize the same expression as equation 3, and a similar approach is used for the conversion to tonnes CO_{2eq}.

$$N_{LchMM} = \left[\sum_s \left[\sum_x (Nx \times NEXx \times MSxs \right) \times \left(\frac{Frac_{LchMs}}{100} \right) xs \right] \times EF \right] \times \frac{44}{28} \tag{5}$$

Here, N_{LchMM} represents indirect N_2O emissions due to leaching and runoff in kg N_2O yr^{-1}. $Frac_{LchMs}$ represents managed manure nitrogen losses percent due to runoff and leaching with a typical value of 20%. EF represents N_2O emission factor due to leaching and runoff (0.0075 kg N_2O–N) [39]. Other elements of the equation symbolize the same expression as equation 3, and a similar approach is for the conversion to tonnes CO_{2eq}.

2.2.2. Cooking energy

The potential of biogas generation was estimated based on equation (6) [42,43,45].

$$LMp = \sum_x Mx \times Rx \times Qx \times Bx \times Max \tag{6}$$

Here, LMp represents CH_4 generation from biogas in m^3 $year^{-1}$; x stands for livestock category and M represents manure generation in kg $year^{-1}$; R represents total solids percentage of the livestock manure; Q represents availability coefficient; B represents the quantity of biogas produced per kg of total solid in m^3 kg^{-1} TS, and Ma stands for biogas methane content percentage. The model parameter of this study is presented in Table 3.

The LMp value was used to estimate the total energy contained in the

Table 3
Model parameter for the biogas generation estimation.

Livestock category	Manure generation		Total solid		Availability coefficient		Biogas production rate		Methane content of the biogas	
	Reported range (kg/head/day)[a]	This study (kg/head/day)	Reported range[b] (%)	This study (%)	Reported value (%)[c]	This study (%)	Reported range (m^3 kg^{-1} TS)[d]	This study (m^3 kg^{-1} TS)	Reported range (%)	This study (%)
Large ruminants (buffaloes and cattle)	10–20 (5–9%)*	17 (9%)*	25–30	30	50	50	0.6–0.8	0.8	50–70[e]	60
Small ruminants (sheep and goats)	2–2.5 (4–5%)	0.8 (4%)	18–25	25	13	13	0.3–0.4	0.4	40–50[f]	45
Poultry	0.08–0.1 (3–4%)	0.045 (3%)	10–29	29	99	99	0.3–0.8	0.8	50–70[g]	60

Sources and notes.
*Values in the parenthesis represent manure generation percentage of body weight/day.
a [42,43,45].
b [42,45].
c [42,43,45].
d [42,45].
e [59–61].
f [42].
g [61,62].

biogas. The calorific value of the biogas was reported as 21.345–22.207 MJ/m^3 (600–650 BTU/ft^3) [47]. This study considered the mean value (21.8 MJ/m^3) of the mentioned range. The study then estimated the equivalent volume of natural gas and LPG that would produce the same energy. The specific energy density of natural gas and LPG considered were 38.7 MJ/m^3 and 95.1 MJ/m^3 [48]. The equivalent emission avoidance was estimated using equation (7).

$$Em_{Avoidance,\ q} = En_{Avoidance,\ q} \times Emf_q \tag{7}$$

Here, $Em_{Avoidance,\ q}$ represents emission avoidance in tonnes CO_{2eq} from the energy substitution by the livestock derives biogas; $En_{Avoidance,\ q}$ represents energy avoidance in MJ; Emf_q represents emission factors of the specific energy type taken from the IPCC 2006 guideline (Table 2.2, chapter 2, volume 2) [49]; q represents avoided energy type. Biogas combustion produces CO_2, but it is biogenic and does not add to GHG emissions [5,6,41].

2.2.3. Electricity

The study estimated electricity generation using equation (8).

$$El_{Biogas} = En_{Biogas} \times \eta \tag{8}$$

Here, El_{Biogas} represents electricity generation quantity in kWh $year^{-1}$; En_{Biogas} is the energy content in kWh $year^{-1}$, and η represents the efficiency percentage of biogas to electricity conversion. Power generation plant type can influence the variation of efficiency value. η value varies from 35 to 42% (large turbine system) and 25% (small generators) [50,51]. The study assumed η value as 30% [42]. En_{Biogas} was calculated using equation (9).

$$En_{Biogas} = SpE_{Biogas} \times LMp \tag{9}$$

Here, is SpE_{Biogas} computed as 6 kWh m^{-3} (based on 21.8 MJ/m^3 biogas calorific value and 1 kWh = 3.6 MJ) [8,42].

The generated electricity will replace the existing fossil fuel based national grid electricity in the urban areas, hence the equivalent emission avoidance from biogas-based electricity generation was estimated using equation (10).

$$Em_{Avoidance,\ e} = El_{Biogas} \times Emf_{electricity\ mix} \tag{10}$$

Here, $Em_{Avoidance,\ e}$ represents emission avoidance in tonnes CO_{2eq} from the electricity substitution by the livestock derived biogas; $Emf_{electricity\ mix}$ represents emission factors of the existing electricity mix of the country in kg CO_{2eq} kWh^{-1}. $Emf_{electricity\ mix}$ computed using equation (11).

$$Emf_{electricity\ mix} = Ef_{coal\ electrcity} \times W_{Coal} + Ef_{gas\ electrcity} \times W_{gas} + Ef_{Oil\ electrcity} \times W_{Oil} + Ef_{Hydro\ electrcity} \times W_{Hydro} \tag{11}$$

Here, *Ef* represents the emission factors of the respective electricity power plant in kg CO_{2eq}/kWh; and W represents the weight of the respective source in the national electricity mix. Bangladesh Power Development Board (BPDB) reported electricity mix of Bangladesh considered in this study as, such as coal-based electricity (3.35%), gas-based electricity (64.91% comprised of 60.69% domestic production and 4.22% imported), hydroelectricity (1.47%), oil-based electricity (30.27%) [52]. The emission factors considered were: 0.91 kg CO_{2eq}/kWh, 0.65 kg CO_{2eq}/kWh [53,54], 0.004 kg CO_{2eq}/kWh [55], 0.778 kg CO_{2eq}/kWh [56] for the electricity based on coal, natural gas, hydropower, and oil, respectively.

2.2.4. Transportation fuel

Most of the motor vehicles in urban areas of Bangladesh now run on CNG [57,58]. The study evaluated the potential biogas use for the urban vehicle fleet using a methodology similar to that mentioned in section 2.3.2.

2.3. Scenario analysis

To evaluate the spectrum of the possible circular economy based urban community resource consumption behavior in Bangladesh from the livestock wastes, the study defined six scenarios. Neither transportation nor infrastructure-related impacts were considered and evaluated both for the business as usual (BAU) analysis and scenario analysis because of relevant nationwide data unavailability of the existing contexts. Five different assumptions were considered. These were (a) in the BAU scenario (scenario A), the existing livestock sector and patterns will adhere to the historical trend, as well as consistent with the existing livestock management system; (b) all other improvement scenarios (scenarios B to F), were consistent with Bangladesh's existing plans for low carbon development as stated by several national documents [28–32]; (c) the livestock manure of each division will be used only for the major urban centers of that respective division; (d) necessary infrastructure like centralized livestock manure collection system, centralized biogas digester system, biogas to electricity generation system, biogas to CNG conversion system will be developed in each respective division; and (e) because of the ongoing policy and strategy deployment efforts for the low carbon economic development, there will be positive regulatory, financial and administrative stimuli both for suppliers and users.

Scenario A: The BAU is represented by the first scenario to depict the ongoing situation. The annual mean growth rate for the period of 1990–2016 was used to project the future livestock population and carbon footprint of the livestock sector till 2050.

Scenario B: This scenario represents the maximal exploitation of livestock manure (100%) through anaerobic digesters to generate biogas for substituting natural gas in the residential sector of the urban areas for cooking purposes.

Scenario C: This scenario represents the maximal exploitation of livestock manure (100%) through anaerobic digesters to generate biogas for substituting LPG in the residential sector of the urban areas for cooking purposes.

Scenario D: This scenario represents the maximal exploitation of livestock manure (100%) through anaerobic digesters to generate biogas for substituting the existing electricity mix in the residential sector of the urban areas.

Scenario E: This scenario represents the maximal exploitation of livestock manure (100%) through anaerobic digesters to generate biogas for substituting natural gas used as CNG in the urban transportation sector.

Scenario F: This scenario represents a combination of scenario B, C, D, and E with the equal share (25%) of generated biogas from livestock manure through anaerobic digesters for substituting natural gas and LPG for residential cooking, existing electricity mix, and CNG in the urban transportation sector.

2.4. Sensitivity assessment

The study assessed the sensitivity of the results considering the uncertainty of the input data. The study assumed low error data with a ±5% possible error margin, intermediate with a ±10% error margin, and high error data with a ±15% error margin. Data taken from published literature, like-journal articles were considered as high error data, such as manure generation rate, the total solid content of the manure, biogas production rate, and energy density of different fuel sources. Data from the BBS and SNC were the national official statistics. So, this study considered such data with less error percentage for our study context, such as-livestock population time-series data, and the bodyweight of livestock. Data from the IPCC GHG inventory guideline were considered as intermediate level data. IPCC emission factors data fall under this category. The input and output were varied based on these error margins to determine the sensitivity range of the projections.

3. Results

3.1. Greenhouse gas emission impacts

3.1.1. Long term emission trends

The mitigation potential of the carbon footprint from the livestock sector significantly depends on an understanding of the baseline levels of emissions, long-term growth trend, key contributing GHG, their key sources, and the regional differences, which are discussed below:

Fig. 1 shows the carbon footprint trends of the principal GHGs (CH_4 and N_2O) of the livestock sector in different emissions categories. The study observed that between 1996 and 2016 carbon footprint from the livestock sector increased by 29%. This study estimates that the livestock sector's carbon footprint in 2016 was 26.55 million tonnes of carbon dioxide equivalent (Mt CO_{2eq}). This emission consists of 89% methane and 11% nitrous oxide.

The trend of CH_4 and N_2O emission from different livestock category presented in Figs. S3 and S4, respectively. The study observed that from 1996 to 2016, enteric fermentation and manure management related CH_4 emissions increased by 30% (Fig. S3). Enteric fermentation

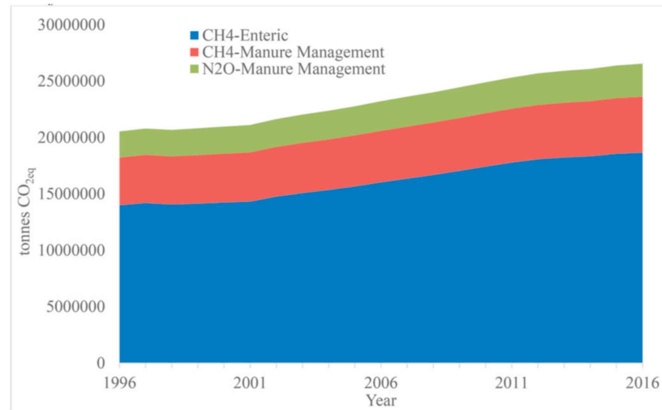

Fig. 1. Carbon footprint in tonnes CO_{2eq} from the livestock sector between 1996 and 2016. Data source: [63,64].

constitutes a major part of CH_4 emission accounting 79%, while manure management accounts for 21% of the total livestock-based CH_4 emissions for the year 2016 (Fig. 1). We estimated that CH_4 emissions from livestock in 2016 were 23.63 Mt CO_{2eq}. The bulk share (94%) of that CH_4 emission is emitted by the two ruminants, cow (56%) and goat (38%). The long-term trend analysis indicates that CH_4 emissions from goat have significantly increased from 5.35 to 9.06 Mt CO_{2eq} with 3.5% annual growth. CH_4 emissions from cow are almost constant from 12.19 to 13.17 Mt CO_{2eq}. Poultry manure has only a 1% share of the total CH_4 emissions (Fig. S3). Besides CH_4, the livestock sector also contributed a small but significant amount of N_2O emission of 2.92 Mt CO_{2eq} during 2016. Cow constitutes a major part of the N_2O emission accounting 72%, while poultry accounts for 23% of the total livestock-based N_2O emission for the year 2016 (Fig. S4).

3.1.2. Regional pattern

Amongst divisions, the highest carbon footprint of 3.55 Mt CO_{2eq} (18.24% of the total emission) was estimated from Rajshahi followed by Rangpur (3.52 Mt CO_{2eq}), Dhaka (2.91 Mt CO_{2eq}), and Khulna (2.91 Mt CO2eq) in 2011. Sylhet division has the least (5.76%) share of the total livestock sector carbon footprint (Table A1). The livestock sector's carbon footprint was further spatially analyzed at the district level. Based on the emission the districts were classified into five categories from very low to very high with an equal class range depending on the maximum and minimum value of considered indicators (emission and emission intensity) for the spatial analysis. Amongst districts for CH_4 emissions, only one district (Dinajpur) falls under the very high emitting category, three districts (Naogaon, Bogra, and Mymensingh) falls under the high category, and ten districts under the moderate category (Fig. 2a). Only one district (Rangpur) falls under the very high emitting category, two districts (Mymensingh and Dinajpur) falls under the low category, and the remaining district categorized as a very low category in terms of N_2O emissions (Fig. 2b). The detailed spatial analysis in terms of CH_4 emission intensity (tonnes CO_{2eq}/sq km) indicated two districts (Naogaon and Jessore) fall under the very high emitting category, while Chittagong, Jhenaidah, and Dinajpur fall under the high emitting category, and 17 districts are classified as under low emitting category (Fig. 2c). The detailed spatial analysis in terms of N_2O emission intensity (tonnes CO_{2eq}/sq km) designated a similar spatial pattern (Fig. 2d).

3.1.3. Economic growth and urbanization impacts on emission trajectories

Economic, population, and urbanization current growth trends are triggering the cities to be considered a hotspot of carbon footprint and opportunities for emission reduction globally [46,65]. The substantial contribution from the food consumption of the urban inhabitants to carbon footprint necessitates the reduction of emission by urban action

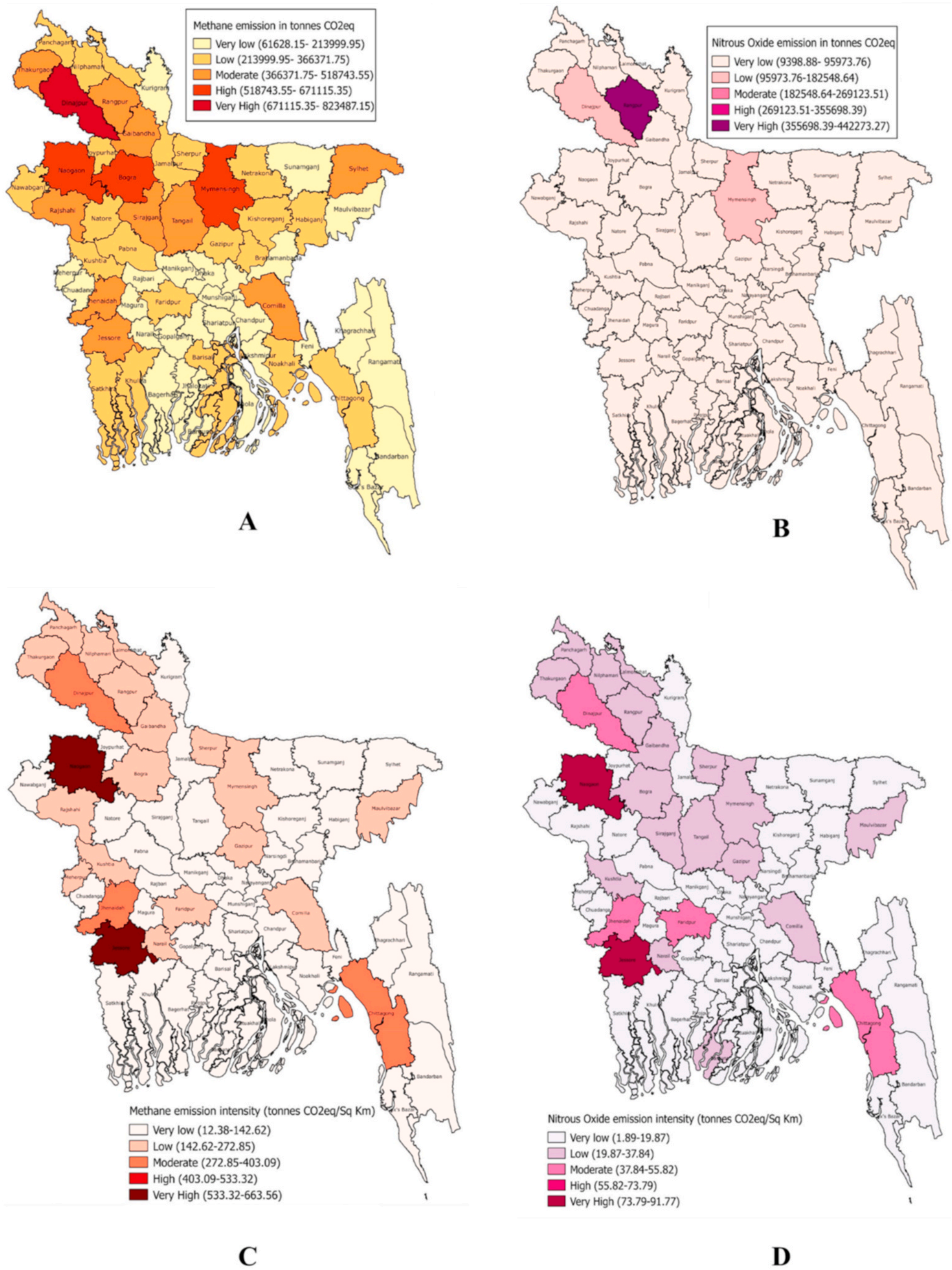

Fig. 2. (A) CH_4, (B) N_20 emission pattern in tonnes CO_{2eq}; and (C) CH_4, (D) N_20 emission intensity in tonnes CO_{2eq}/sq km across the 64 districts of Bangladesh for the year 2011. Source: Authors analysis.

[1,66]. Because of the urbanization and affluence impact on livestock and food sector carbon footprint [65], this study explored the economic growth and urbanization impacts on livestock sector carbon footprint trajectories.

The impact of economic growth on livestock sector carbon footprint analyzed in terms of gross domestic product (GDP), GDP growth rate, and agricultural sector GDP; while the impact of urbanization analyzed in terms of per capita income and urban population as shown in Figure B1 (the shaded area represents the confidence interval of the best-fit line at 95% level). The GDP ($r = 0.93$ with $p = 1.1e\text{-}09$), agricultural GDP ($r = 0.93$ with $p = 1.6e\text{-}09$), per capita income ($r = 0.93$ with $p = 8.6e\text{-}10$), and urban population ($r = 0.99$ with $p = 2.2e\text{-}16$) exhibited a strong and significant correlation to the increasing trajectories of livestock sector carbon footprint, in comparison with GDP growth ($r = 0.72$ with $p = 2.1e\text{-}04$). Figure B1 shows for the increase of \$1 GDP value, 1% GDP growth rate, \$1 agricultural GDP, \$1 per capita income, and one urban inhabitant in the country; the livestock sector carbon footprint increased by 3.79×10^{-5}, 1.65×10^{6}, 2.95×10^{-4}, 6.78×10^{3}, 2.22×10^{-1} tonnes CO_{2eq}, respectively.

3.2. Climate change mitigation benefits of circular economy-based resource consumption

Fig. 3 shows future carbon footprint trajectories for the six scenarios including the BAU. Fig. 4 shows the estimates of carbon footprint avoidance potential of circular economy-based resources consumption behaviour in the cities of Bangaldesh in 2050 relative to 2016.. In the BAU scenario, the carbon footprint will continue to grow year after year,

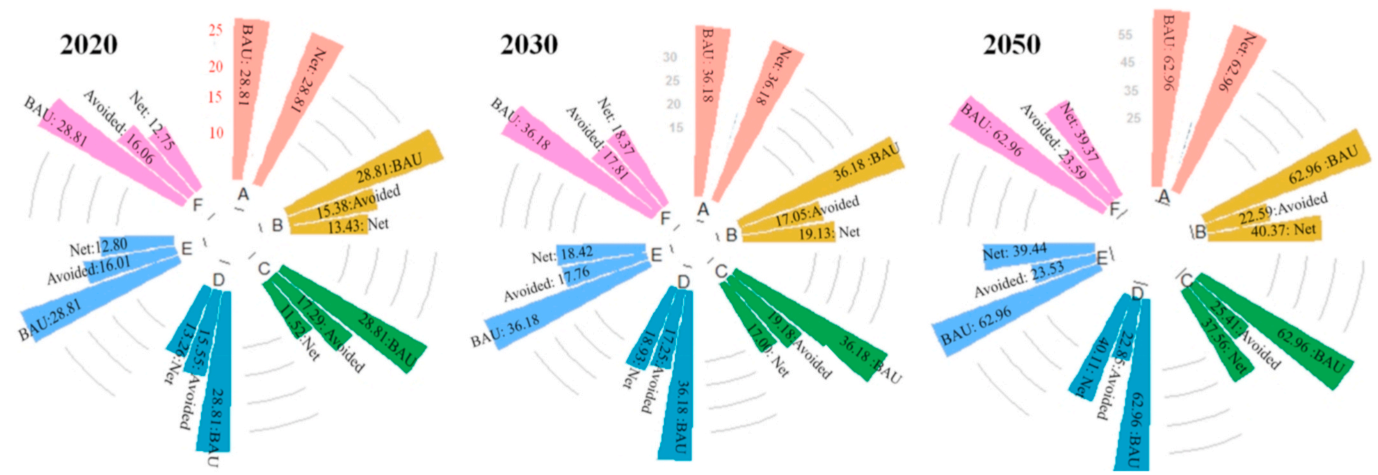

Fig. 3. Carbon footprint under different scenarios of livestock manure-based renewable energy use in the urban community of Bangladesh from 2020 to 2050 in Mt CO_{2eq}. Source: Authors analysis.

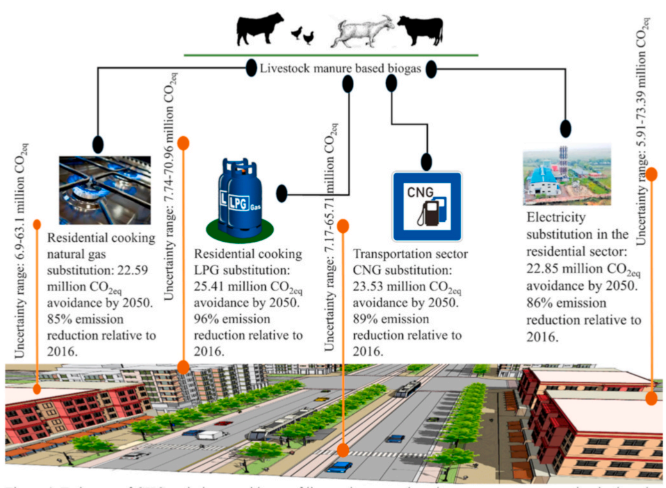

Fig. 4. Carbon footprint avoidance potential in the cities of Bangladesh from circular economy-based resources consumption behaviour.

increasing from 26.55 Mt CO_{2eq} in 2016 to 62.96 Mt CO_{2eq}, a growth of 2.37 times. In the LPG substitution scenario for residential cooking (C scenario), the carbon footprint avoidance is maximum in 2020 (17.29 Mt CO_{2eq}), 2030 (19.18 Mt CO_{2eq}), and 2050 (25.41 Mt CO_{2eq}). Hence, this scenario represents the least net carbon emission from 2020 to 2050. Almost similar carbon footprint avoidance potential and net emission performance is observed for the CNG substitution of the existing urban transport system (E scenario) and scenario F, which is a combination of substituting natural gas and LPG for residential cooking, existing electricity mix, and CNG in the urban transportation sector with equal (25% for each measure) exploitation of the livestock sector manure (Fig. 3). So, the substitution of existing residential cooking by LPG in the urban areas, and CNG substitution of the existing urban transport system can counterbalance the national carbon footprint in 2050 by 96% and 89%, respectively relative to the 2016 emission level (Fig. 4). Equal utilization of the livestock manure for a combined measure of climate-friendly renewable energy use in an urban community in the form of substituting natural gas and LPG for residential cooking, existing electricity mix, and CNG in the urban transportation sector can also counterbalance the national carbon footprint in 2050 by 89% relative to 2016 emission level.

Climate-friendly renewable energy development potential is analyzed at the division level, which is named after the major city within its jurisdiction. The potential of carbon footprint avoidance in the 8 division under different scenarios of climate-friendly renewable energy sources for the urban community in 2030 and 2050 is shown in Tables 4 and 5, respectively. TThe substitution of LPG for residential cooking (scenario C), the substitution of CNG for the urban transport system (scenario E), and the combined measures (scenario F) can result in the highest carbon footprint avoidance in Rajshahi (3.38, 3.13 and 3.14 Mt CO_{2eq}, respectively) followed by Chittagong (3, 2.79 and 2.80 Mt CO_{2eq}, respectively) in 2030. By 2050, carbon footprint avoidance in both divisions will be 32–33% higher in different scenario compared to the 2030 level. Carbon footprint avoidance in Dhaka, Khulna, and Rangpur by 2030 will be more than 2 Mt CO_{2eq} for the studied scenarios, while it may reach more than 3 Mt CO_{2eq} by 2050 (Tables 4 and 5).

3.3. Sensitivity analysis

The sensitivity range of potential carbon footprint avoidance in the 8 divisional cities under different scenarios is presented in Appendix C (Table C.1 and C.2). This assessment of carbon footprint avoidance and renewable energy from the livestock sector is subject to various uncertainties, such as animal numbers, climate, simplifications of livestock feed, manure treatment process, aggregation of different types (dairy and non-dairy cattle and buffalo) of livestock, and emission factors [67]. Emissions factors related uncertainties are supposed to be highest [39].

A large number of assumptions influenced the scenarios studied here, such as electricity mix, natural gas use, LPG use, and livestock manure-based biogas generation and conversion model. Their assumptions can influence the scenario results. If any underlying hypotheses of used

Table 4
Potential of carbon footprint avoidance in the 8 divisional cities under different scenarios of livestock manure-based renewable energy consumption in the urban community of Bangladesh in 2030.

Division	Studied scenarios					
	A	B	C	D	E	F
	Million tonnes CO_{2eq}					
Barisal	3.65	1.72	1.93	1.74	1.79	1.80
Chittagong	5.68	2.68	3.01	2.71	2.79	2.80
Dhaka	5.01	2.36	2.65	2.39	2.46	2.46
Khulna	5.48	2.58	2.91	2.61	2.69	2.70
Mymensingh	3.00	1.42	1.59	1.43	1.47	1.48
Rajshahi	6.37	3.00	3.38	3.04	3.13	3.14
Rangpur	5.01	2.36	2.66	2.39	2.46	2.47
Sylhet	1.97	0.93	1.04	0.94	0.97	0.97

Source: Authors analysis.

Table 5
Potential of carbon footprint avoidance in the 8 divisional cities under different scenarios of livestock manure-based renewable energy consumption in the urban community of Bangladesh in 2050.

Division	Studied scenarios					
	A	B	C	D	E	F
	Million tonnes CO_{2eq}					
Barisal	6.35	2.28	2.56	2.30	2.37	2.38
Chittagong	9.89	3.55	3.99	3.59	3.70	3.71
Dhaka	8.71	3.13	3.52	3.16	3.26	3.26
Khulna	9.54	3.42	3.85	3.46	3.57	3.58
Mymensingh	5.23	1.88	2.11	1.90	1.95	1.96
Rajshahi	11.09	3.98	4.47	4.02	4.14	4.15
Rangpur	8.73	3.13	3.52	3.17	3.26	3.27
Sylhet	3.43	1.23	1.38	1.24	1.28	1.28

Source: Authors analysis.

models (e.g. biogas generation and conversion model) are changed the scenario results may vary. However, the goal of the scenario projection of this study is not to predict; rather to provide a likely indication of future reduction of livestock sector carbon footprint from circular economy-based resource consumption behaviour in cities. If the stated assumptions like biogas generation and conversion model, the energy value of the natural gas, LPG, and carbon footprint of the existing electricity mix hold; circular economy based cities in Bangladesh can be adaptable. The scenario analysis intends to provide the possible trajectories, rather than stating an absolute value.

3.4. *Policy regime in Bangladesh on renewable energy from livestock waste*

The country formulated the first Renewable Energy Policy in 2002 to finance renewable energy and incentives in the form of an income tax rebate to attract foreign investors. Later, the Renewable Energy Policy of Bangladesh (2008), set a 5% renewable energy generation target by 2015, and 10% by 2020. Sustainable and Renewable Energy Development Authority (SREDA) was formulated in 2012 to coordinate country wide renewable energy generation and projects. The renewable energy generation target set by Renewable Energy Policy (2008) also reaffirms by this act. Besides, the 7th Five Year Plan (2015) also encourages research and investment in the ocean, tidal, and geothermal energy development. Later, Power Sector Master Plan (PSMP), 2016 set out a comprehensive renewable energy development plan of 2470 MW by 2021, and 3864 MW by 2041. Table 6 presents a brief description of the enabling environment of renewable energy development in the country.

4. Discussion

4.1. *Comparison with other countries livestock waste to renewable energy generation policies to adopt circular economy*

Livestock manure-based biogas generation is growing gradually in Bangladesh, in comparison with countries like China, India, Nepal, Vietnam as reflected in Table 7. According to renewable energy statistics, Germany is the leading country (6754 MW) globally for biogas-based electricity generation, and China (630 MW) is in the leading position in Asia [73]. That is why this study compared the livestock waste-based renewable energy generation policies of Bangladesh with Germany, China, and India as a neighboring country (Table 8). Though Bangladesh has a generic fiscal and tariff policy related to renewable energy as mentioned in Table 6, none is specific to biogas-based electricity generation. Subsidies are available at the household level ranging from US$60–250 for biogas plant construction. Varying amount of loan is also available with a 6–11% interest rate for a period of 3 months–7 years (Table 8).

While in Germany, the Renewable Energy Sources Act (EEG) ensures the preferential purchase obligation, grid connection right, a guaranteed minimum feed-in tariff, and biogas upgrading bonus for renewable energy generation from livestock manure. Also, small farms in Germany can receive up to US$0.27/kWh electricity from biogas [74]. In China, there exists coherent law related to agriculture, animal husbandry,

Table 6
Enabling environment of renewable energy development in Bangladesh.

National strategies	Examples	Comments
Regulatory regime	National Energy Policy (NEP), 1996	It emphasized the exploration, and production of energy on a sustainable basis.
	Renewable Energy Policy of Bangladesh, 2002	Assigned the government agencies responsibilities to finance renewable energy and provide financial incentives in the form of income tax rebates to attract foreign investors.
	Renewable Energy Policy of Bangladesh, 2009	For the first time set a target of 5% renewable electricity generation by 2015, and 10% by 2020.
	Sustainable and Renewable Energy Development Authority Act, 2012	SREDA was formulated to coordinate countrywide renewable and renewable energy activities and projects.
	Power Sector Master Plan (PSMP), 2016	Proposed a comprehensive renewable energy development plan of 2470 MW by 2021, and 3864 MW by 2041.
Financial incentives	Corporate Bonds	Renewable energy companies can issue corporate bonds with the approval from the Securities and Exchange Commission (SEC), Bangladesh [33,68].
	Discounted share price	To ensure a higher rate of return renewable energy companies can issue shares at a 10% discount price of its face value [69].
	Power purchase	Government power utility companies through mutually agreed Power Purchase Agreement (PPA) are obliged to purchase electricity from grid-connected renewable energy companies [70].
	VAT benefits	Renewable energy investors are exempted from customs duties up to 15% along with other charges like import permit fees for imported renewable energy equipment [69].
	Electricity price	The government will not regulate renewable electricity prices, rather it will be negotiated between renewable energy companies and government power utility companies [71].
	Income Tax	Renewable energy companies are allowed for 15 years corporate income tax rebate, and can claim 100% depreciation in the first year (solar thermal, solar photovoltaic), and first five years (wind, small hydro, biomass, tidal, and geothermal) [33].
Tariff policy	Solar rooftop and Green energy	Any renewable energy projects up to 5 MW capacity or more can claim renewable energy tariffs. This allowed consumers to co-finance their electricity bills [72].
	Net Energy Metering	Consumers and producers can connect the renewable energy system to the national grid based on drafted net energy metering guidelines (2017) [71].

Source: Authors analysis.

Table 7
Overview of biogas digester feedstock and number in selected Southeast Asian countries.

Country	Feedstock	First digester installation year	Installed plant	References
China	Pigs, cows, chickens manure	1921	42,000,000	[79]
India	Livestock manure	1900	5,000,000	[80]
Nepal	Cow manure	1955	270,000	[81]
Vietnam	Pig manure	1964	500,000	[81]
Bangladesh	Cow and buffalo manure	1972	~100,000	[23]
Cambodia	Combination of pig manure and cow manure	1986	20,000	[[81]

Source: Authors analysis.

renewable energy, bioenergy development, circular economy, and rural biogas projects. These law and policies are combined with favorable finance strategies like (i) providing interest-free loans of around US $2937/100 m^3 capacity to biogas plants (small, medium, and large), and (ii) 25%–45% subsidy of the total biogas projects cost [75,76]. It seems that Germany and China are promoting commercial biogas generation from livestock wastes and organic feedstock through preferential purchase, grid connection right, and a minimum feed-in tariff; which is currently absent in Bangladesh. Other successful countries for promoting commercial biogas generation are Italy, the UK, and the USA. Italy is promoting electricity generation from livestock wastes based biogas by a high feed-in-tariff of US$ 0.31/kWh with a capacity of less than 1 MW for 20 years. A similar kind of strategy is also in place in the UK. While, in the USA federal and state governments are promoting commercial biogas projects through soft loans, tax incentives, grants, and performance-based incentives. For example, (i) in Iowa there exists tax credits of US$0.015/kWh for 10 years; (ii) 25–50% of total biogas plant project costs are available as grants in Oregon and Pennsylvania; (iii) in Massachusetts 75% and 25% of costs available as grants for design-phase, and construction-phase, respectively; and (iv) incentives scheme of US$0.015–0.1/kWh for biogas-based electricity generation also available in other states [77,78].

4.2. Policy implications

The government should formulate long-term goals and strategies for circular economy-based cities in the country. The study argues that formulating a timely policy and institutional framework can help the country in this aspec as suggested in a recent study [16]. The proposed solutions are:

a. Policies and strategies could be in the form of incentives scheme per kWh electricity, quota obligations, preferential purchase, grid access, grants, and feed-in tariff. Though there exists a loan scheme to the investor, those are repulsive.
b. Bangladesh can learn from the experience of Germany on how to continuously updates policy and strategies for biogas-based electricity generation. An incentive to the biogas energy generator can be given in the form of "Green Pricing" similar to Denmark.
c. The current renewable electricity generation target covers all renewable sources. That is why, dedicated biogas based renewable energy generation targets is needed for the circular economy-based cities in Bangladesh. For example, (i) 5% of electricity from livestock manure-based biogas by 2030 and 15% by 2050, (ii) 10% of cooking energy from livestock manure-based biogas by 2030 and 25% by 2050, and (iii) 10% of public buses in the urban area will be run by livestock manure-based biogas by 2030 and 15% by 2050.
d. The feed-in tariff, quota obligations, and grid access can also accelerate the process of circular economy based cities in the country.

Table 8
Comparison of policies and measures of livestock waste-based renewable energy generation with selected countries.

selected countries	Policy and law	Financial assistance/ subsidy/Loan	References
Bangladesh	Renewable energy companies can issue shares at a 10% discount price of its face value, and government power utility companies through mutually agreed PPA are entitled to purchase electricity from grid-connected renewable energy projects. Any renewable energy companies are exempted from corporate income tax for 15 years and entitled up to 100% depreciation in the first year. Renewable energy investors are exempted from customs duties/ import permit fees up to 15% for imported renewable energy equipment.	Subsidies at the household level ranging from US$60-250 for the biogas plant. IDCOL also provides 80% loans to a household for financed biogas plant through participating organization with a 6% interest rate for 7 years with a 1-year grace period. Under the Bangladesh Bank financing scheme, any single/Joint Family/ Enterprise is eligible to get a loan of US$300-30000 with a 9-11% interest rate for a period of 3 months to 5 years.	[33, 36, 82, 83]
China	The country has enacted five main laws to promote the biogas industry (e.g. agricultural law, renewable energy, animal husbandry, energy conservation, and circular economy). Also, the energy policies include the 12th Five-Year Plan for Bioenergy Development and the Rural Biogas Projects.	Interest-free loans of around US$2937 for both small, medium, and large biogas plants per 100 m^3 capacity. 25% to 45% of the biogas project cost is available as subsidies.	[75, 76]
India	Electricity distribution companies need to procure 100% electricity from waste to energy plants based on the 2018 tariff policy. A generic tariff of $0.1/KWh of electricity for the biogas project is declared in 2018, and the policy order provided detailed guidelines on return on equity, interest rate, capital and working cost, and depreciation.	US$106-352 subsidy per biogas plant with a capacity of 1-25 m^3 under the National Biogas and Organic Manure Programme (NNBOMP). US$352-493 subsidy per plant for a biogas plant with a capacity of 3-250 Kw under Biogas Power Generation (Off-grid) and Thermal energy application Programme (BPGTP).	[84, 85]
Germany	The Renewable Energy Sources Act (EEG) (with multiple revisions) serving as a guideline for renewable energy developers related to the preferential purchase, right of grid connection, and a guaranteed minimum Feed-in tariff. Biogas generation is boomed in Germany following the introduction of a biogas upgrading bonus in 2009.	Small farms in Germany can receive up to US $0.27/kWh electricity from biogas.	[74]

Source: Authors analysis.

Similar to China support for interest-free energy loans with regular and stringent monitoring for livestock waste-based commercial biogas plants can catalyze the progress.

e. Coherent law focusing on Agricultural, Renewable Energy, Animal Husbandry, and Circular Economy can also accelerate the livestock manure-based energy use to ensure circular economy-based cities in Bangladesh.

The barriers to be addressed to materialize the proposed solutions are:

a. The key barrier for a wide-scale and centralized system adoption of renewable energy from livestock wastes at commercial scales is the investments need; so associated investment cost-benefits analysis is required.
b. The country has little experience of centralized biogas production because most of the existing biogas projects are at household scales in rural areas. So, the widespread diffusion of biogas technology at commercial scales is absent. Therefore, outreach programs are needed to promote centralized biogas technology in the cities.
c. The outreach program should cover collection, update and increase dissemination of regionalized livestock data, foster research on methane capture and utilization, and disseminate and adoption of anaerobic digestion technological models. These can be guided by the urban management authority through a public-private partnership with different modernization levels and sizes.

5. Conclusions

This study has explored the (i) pattern and regional variation in GHG emissions from the livestock sector, (ii) climate change mitigation benefits of circular economy-based resource consumption from livestock waste-based biogas use in the urban areas of Bangladesh, and (iii) policies and measures driving the renewable energy generation from livestock wastes. By using Bangladesh's livestock sector as a case, standard GHG emission and energy generation model was applied to explore the above objectives. From the study following conclusions can be drawn:

- First, there seems to be a positive correlation between livestock sector GHG emissions and economic growth in Bangladesh. For example, an increase of $1 GDP, 1% GDP growth, $1 agricultural GDP, and $1 per capita income resulting in an increase of carbon footprint from livestock sector by 3.79×10^{-5}, 1.65×10^{6}, 2.95×10^{-4}, and 6.78×10^{3} tonnes CO_{2eq}, respectively.
- Second, based on the results of the five progressive scenarios, the study finds that the LPG substitution scenario for residential cooking showed the highest national carbon footprint avoidance in 2020 (17.29 Mt CO_{2eq}), 2030 (19.18 Mt CO_{2eq}), and 2050 (25.41 Mt CO_{2eq}). Hence, this scenario represents the least net GHG emissions from 2020 to 2050. Therefore, the Government should provide soft loans/subsidies, or encourage the NGOs to provide soft loans to low-income households residing in urban and sub-urban areas to adopt livestock manure-based biogas to substitute natural gas/LPG for residential cooking; and encourage CNG driven taxi and private car to adopt livestock waste-based biogas fuel.
- PPromoting the biogas generation from livestock wastes through commercial biogas scheme is currently absent in Bangladesh. Most of the existing financial schemes and subsidy programs are dedicated to the household level. It seems that the existing loan term is repulsive to the investors. A dedicated biogas-based energy generation target for the urban areas along with feed-in tariff, quota obligations, and grid access can accelerate the process.

Bangladesh's transition to a circular economy-based cities requires the policy integration of residential cooking fuel, existing fossil fuel-based electricity, and urban transportation fuel substitution by livestock manure-based biogas. This in turn will reduce the national GHG emissions, and enhance energy security through renewable energy generation. Such an approach will provide two folds direct benefits to Bangladesh, i.e., climate change mitigation and energy source diversification. Moreover, as a whole, the country will be also able to advance contribution towards SDGs 'affordable and clean energy', 'sustainable cities and communities', 'responsible consumption and production', and 'climate action'. Depending on the socioeconomic and energy dependence condition, our findings can be applicable to countries alike. This study recommends a pilot-based case study for any divisional city in the country following the methodological approach used in this study, and associated cost-benefit analysis to evaluate the economic aspects of the initiative.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendices

Appendix A. Division wise carbon footprint estimates

Table A1
Division wise estimates of livestock methane, nitrous oxide, and CO_2 equivalent emission for the year (2011)

Division	Livestock population (millions)	CH_4 emission from enteric fermentation (tonnes)	CH_4 emission from manure management (tonnes)	N_2O emission from manure management (tonnes)	CO_{2eq} emission (million tonnes)	Contribution to CO_{2eq} emission (%)
Barisal	18.99	23559.00	9350.41	642.51	1.31	6.73%
Chittagong	29.57	41993.89	16663.40	1113.12	2.33	11.97%
Dhaka	26.05	54208.81	20201.59	1286.61	2.91	14.95%
Khulna	28.54	55699.30	19216.61	1226.32	2.91	14.95%
Mymensingh	15.63	33237.61	12705.60	809.19	1.80	9.25%
Rajshahi	33.15	68576.65	23111.47	1458.61	3.55	18.24%
Rangpur	26.09	66298.02	24111.89	1499.44	3.52	18.09%

(*continued on next page*)

Table A1 (*continued*)

Division	Livestock population (millions)	CH_4 emission from enteric fermentation (tonnes)	CH_4 emission from manure management (tonnes)	N_2O emission from manure management (tonnes)	CO_{2eq} emission (million tonnes)	Contribution to CO_{2eq} emission (%)
Sylhet	10.25	20192.11	8148.91	525.12	1.12	5.76%
Total	188.27	363765.39	133509.88	8560.92	19.46	

Appendix B. The impact of economic growth and urbanization on livestock sector carbon footprint

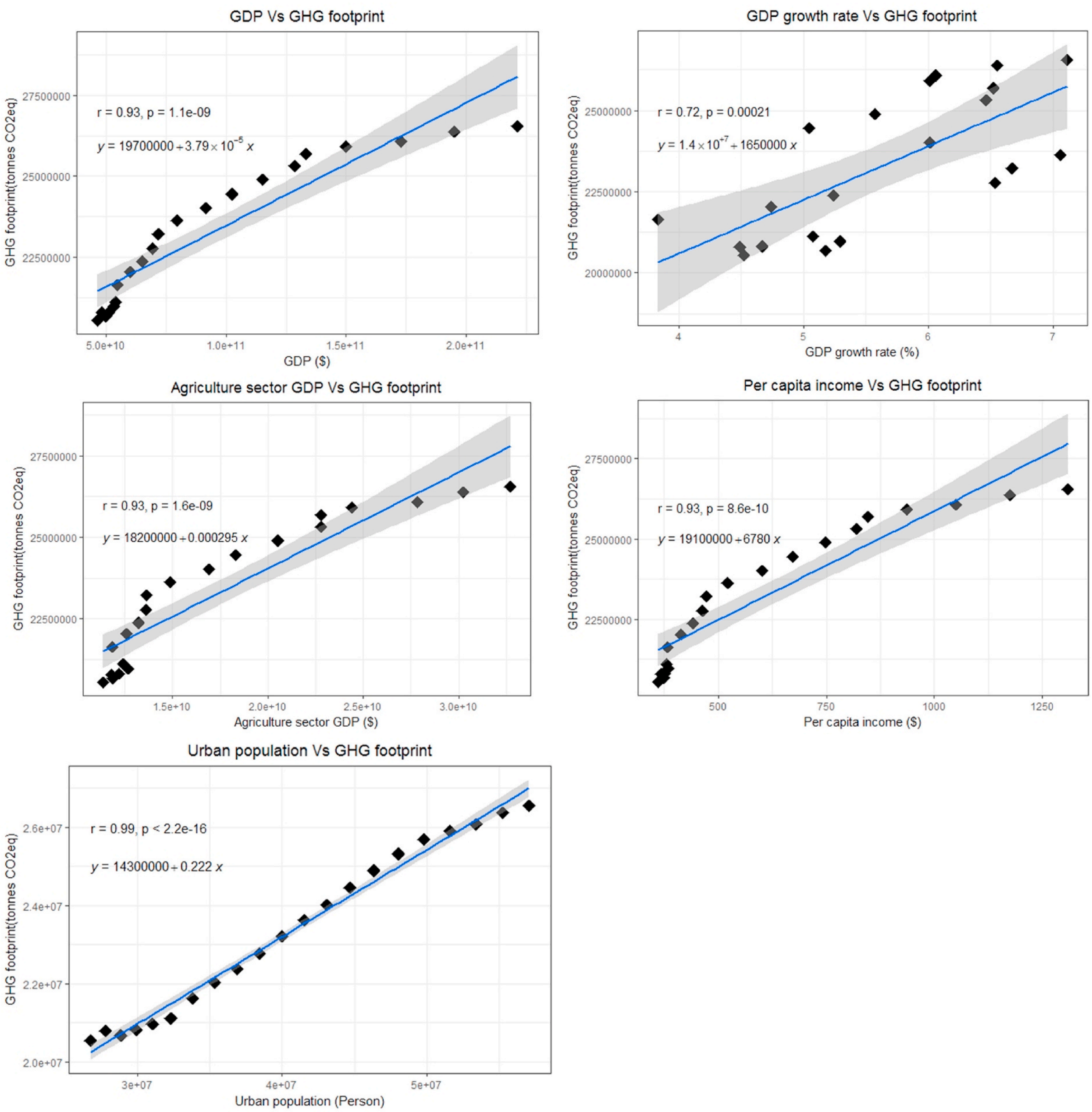

Fig. B1. Impact of economic growth and urbanization on the livestock sector carbon footprint trajectories.

Appendix C. Sensitivity range of potential carbon footprint avoidance in the 8 divisional cities under different scenarios

Table C1
Division wise sensitivity range of potential carbon footprint avoidance for the year 2030 under different scenarios.

Division	A		B		C		D		E		F		Unit
	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	
Barisal	3.12	4.21	0.52	4.80	0.59	5.40	0.45	5.59	0.55	5.00	0.53	5.20	Million tonnes CO_{2eq}

(*continued on next page*)

Table C1 (*continued*)

Division	A		B		C		D		E		F		Unit
	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	
Chittagong	4.86	6.56	0.82	7.48	0.92	8.41	0.70	8.70	0.85	7.79	0.82	8.10	Million tonnes CO_{2eq}
Dhaka	4.28	5.78	0.72	6.59	0.81	7.41	0.62	7.66	0.75	6.86	0.72	7.13	Million tonnes CO_{2eq}
Khulna	4.69	6.33	0.79	7.22	0.89	8.12	0.68	8.40	0.82	7.52	0.79	7.81	Million tonnes CO_{2eq}
Mymensingh	2.57	3.47	0.43	3.95	0.48	4.45	0.37	4.60	0.45	4.12	0.43	4.28	Million tonnes CO_{2eq}
Rajshahi	5.45	7.36	0.91	8.39	1.03	9.43	0.79	9.75	0.95	8.73	0.92	9.08	Million tonnes CO_{2eq}
Rangpur	4.29	5.79	0.72	6.60	0.81	7.42	0.62	7.68	0.75	6.87	0.72	7.14	Million tonnes CO_{2eq}
Sylhet	1.68	2.27	0.28	2.59	0.32	2.92	0.24	3.02	0.29	2.70	0.28	2.81	Million tonnes CO_{2eq}

Table C2
Division wise sensitivity range of potential carbon footprint avoidance for the year 2050 under different scenarios

Division	A		B		C		D		E		F		Unit
	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	
Barisal	5.43	7.34	0.69	6.36	0.78	7.16	0.60	7.40	0.72	6.63	0.70	6.89	Million tonnes CO_{2eq}
Chittagong	8.46	11.42	1.08	9.91	1.22	11.15	0.93	11.53	1.13	10.32	1.09	10.73	Million tonnes CO_{2eq}
Dhaka	7.45	10.06	0.95	8.73	1.07	9.82	0.82	10.15	0.99	9.09	0.96	9.45	Million tonnes CO_{2eq}
Khulna	8.16	11.02	1.04	9.57	1.17	10.76	0.90	11.13	1.09	9.96	1.05	10.35	Million tonnes CO_{2eq}
Mymensingh	4.47	6.04	0.57	5.24	0.64	5.89	0.49	6.09	0.59	5.46	0.57	5.67	Million tonnes CO_{2eq}
Rajshahi	9.48	12.80	1.21	11.11	1.36	12.49	1.04	12.92	1.26	11.57	1.22	12.02	Million tonnes CO_{2eq}
Rangpur	7.46	10.08	0.95	8.74	1.07	9.83	0.82	10.17	0.99	9.11	0.96	9.46	Million tonnes CO_{2eq}
Sylhet	2.93	3.96	0.37	3.44	0.42	3.86	0.32	4.00	0.39	3.58	0.38	3.72	Million tonnes CO_{2eq}

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2020.110695.

Author contribution

K M Nazmul Islam: Conceptualization, Methodology, Software, Writing – original draft, Investigation, Visualization. Tapan Sarker: Conceptualization, Writing- Reviewing and Editing. Farhad Taghizadeh-Hesary: Conceptualization, Writing- Reviewing and Editing. Anashuwa Chowdhury Atri: Data curation, Investigation. Mohammad Shafiul Alam: Writing- Reviewing and Editing.

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