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Sustainable biogas production potential in Nepal using waste biomass: a spatial analysis

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Abstract

Biogas plays a significant part in replacing solid biomass and fossil fuels for cooking. However, the implementation of appropriate policies to promote the development of biogas plants is hindered by a lack of adequate assessment of the biogas potential in Nepal. Thus, we estimate the potential of biogas production at the district level of Nepal from available waste biomass, including livestock manure, agricultural residues, and organic fraction of municipal solid waste (OFMSW). Our estimates show the theoretical potential of biogas production from livestock manure of 1,890 million m^3 $year^{-1}$, agricultural residues of 2,290 million m^3 $year^{-1}$, and OFMSW of 234 million m^3 $year^{-1}$. The total biogas production is 4,412 million m^3 $year^{-1}$, equivalent to 153 million liquefied petroleum gas (LPG) cylinders yearly. Using this biogas potential to replace LPG and solid biomass for cooking could result in avoided CO_2, CO, and $PM_{2.5}$ emissions of 6.3 million tons $year^{-1}$, 0.4 million tons $year^{-1}$, and 0.04 million tons $year^{-1}$, respectively. Our findings suggest that the Terai districts of Morang, Sunsari, Saptari, and Banke, as well as the Hilly districts of Kavrepalanchok, Dhading, and Nuwakot, have a significant amount of biogas-producing potential. Utilising this potential could also contribute to achieving several Sustainable Development Goals and a clean cooking energy transition in Nepal. For this, governments need careful planning, designing, policy support, and facilitation on bio-resource management and utilisation at the local level.

Keywords: Spatial analysis, clean cooking transition, energy policy, biogas, greenhouse gas, sustainable development goal

1. Introduction

In 2020, fossil fuels contributed 79% of the global energy mix (IEA, 2021). They are the primary driver of climate change (Supran et al., 2023), leading to adverse social, economic, and environmental impacts worldwide. Therefore, there is a need for the transition towards renewable and clean energy, which is widely acknowledged. This need is also reflected in the 2030 Agenda for Sustainable Development. Mainly, Sustainable Development Goal (SDG) 7 aims to deliver affordable, reliable, sustainable, and modern energy services for everyone (McCollum et al., 2017). Achieving this goal requires a rapid transition towards renewable and clean energy from the local to global levels. However, the energy transition pathways vary worldwide depending on the current energy mix of countries.

For example, Nepal, an agricultural country, depends on solid biomass, e.g., firewood, livestock manure, and agricultural residues, as the primary energy source. In the fiscal year 2020/21, solid biomass, fossil fuels (e.g., coal and oils), and modern renewable sources (e.g., hydropower and solar) contributed 69%, 28%, and 3% of Nepal's energy mix, respectively. Among the solid biomass, firewood (62%) accounts for the highest share, followed by cow and buffalo dung (3%) and agricultural residues (3%) (Ministry of Finance (MoF), 2021). Overall, 67% of households in the country, more than 80% of rural households, and above 40% of urban households still rely on burning solid biomass for cooking (Paudel et al., 2021). Solid biomass usage that is unsustainable and inefficient entails a wide net of degradation, affecting the environment, human well-being, and long-term socioeconomic advancement. These energy practices take a substantial toll on the planet and its inhabitants, from the immediate concerns of indoor air pollution and localized ecological destruction to the looming threat of global climate change.

Despite limited global greenhouse gas emissions, Nepal grapples with high climate vulnerability, heavily impacting rural communities dependent on temperature-sensitive resources (Suman, 2021). However, opportunities exist within Nepal's resources. Biogas generation from ubiquitous waste biomass holds significant promise for transitioning towards a more sustainable energy landscape (Lohani et al., 2023). Biogas provides clean energy for cooking and space heating, enabling rural and urban communities to reduce their reliance on fossil fuels (Lohani, Dhungana, et al., 2021). Liquefied petroleum gas (LPG), an imported fuel, is becoming increasingly common in urban and rural households. Despite the complexities of transporting LPG, particularly in rural areas with limited infrastructure, its consumption has increased more than twice over the past decade (Water and Energy Commission Secretariat (WECS), 2022). Despite the urgency to diversify its energy mix to move towards energy independence, Nepal's energy policies and practices fail to address it, resulting in the dominance of LPG and solid biomass in cooking (Lohani et al., 2023; Neupane et al., 2022).

The anaerobic digestion (AD) of biomass for producing biogas has emerged as one of the most promising renewable clean energy sources globally (Lohani, Keitsch, et al., 2021) Biogas can reduce the emissions of greenhouse gases (GHG) and air pollutants, such as carbon monoxide (CO) and fine particles ($PM_{2.5}$), by substituting liquefied petroleum gas (LPG) and solid biomass for cooking (Afrane & Ntiamoah, 2011; Gross et al., 2017). Biogas can also produce electricity, and purified and compressed biogas (i.e., CBG) can be used for transportation (Black et al., 2021). Furthermore, due to a high concentration of plant nutrients, digestate, a byproduct of AD, can be utilised as organic fertilizer (Lohani et al., 2023). Doing so helps to bring additional economic benefits to farmers by reducing the need for chemical fertilisers (Thompson et al., 2013). Biogas as clean cooking energy could help avoid deforestation (Katuwal & Bohara, 2009) and improve the health and well-being of women and children because of reduced indoor air pollution and saving time for collecting firewood (Yasar et al., 2017). However, a spatial analysis of these multiple benefits of promoting biogas is missing for Nepal.

Reduced quantity of waste biomass, which would otherwise result in environmental issues, is another significant benefit of biogas (Uçkun Kiran et al., 2016). Biomass dumped in landfills emits methane, a greenhouse gas even more potent than carbon dioxide while decaying, which could be captured and reused using AD for waste treatment (Pradhan, 2023b). Waste biomass comes in many forms. They include livestock manure, agricultural residues, and the organic fraction of municipal solid waste (OFMSW). When handled inappropriately, these wastes pose a severe threat to the environment and public health. By runoff or seeping into soils, pathogens, chemicals, antibiotics, and nutrients found in the waste can pollute surface and ground waterways (Kieliszek et al., 2020). Furthermore, vast volumes of methane are also produced as organic wastes break down. Similarly, burning agricultural residues and municipal waste contributes to increased levels of carbon dioxide in the atmosphere (Stockwell et al., 2016). With agricultural mechanisation, managing crop residues is challenging in the southern plains of Nepal, the Terai region, which is the hub for crop production. There, agricultural residues are usually openly burned in the field.

This open burning significantly contributes to ambient air pollution, especially in the winter season (Budhathoki, 2021).

So far, Nepal has installed nearly 432,000 household biogas plants in 66 of 77 districts (Lohani et al., 2022). Regarding commercial biogas plants of 3,000 to 4,000 m^3 digester size, eight plants are already in operation, and about 14 plants are under construction. Moreover, 200,000 households and 500 large-scale biogas plants have been planned for installation as part of the Second Nationally Determined Contribution (SNDC) to mitigate climate change (GoN, 2020). Implementing this plan requires understanding the spatial distribution of Nepal's biogas potential. Although studies on biogas in Nepal are available, none have conducted the necessary spatial analysis at the national scale. Some investigate the waste-to-energy potential, temperature effects on AD, and co-digestion of food waste with cattle manure, poultry litter, and sewage sludge at various mixing ratios and ambient temperature conditions (Dhungana et al., 2022; Dhungana & Lohani, 2020; Lama et al., 2012; Lohani et al., 2018; Lohani, Keitsch, et al., 2021; Lohani, Shakya, et al., 2021). Others discuss electricity generation opportunities from large-scale biogas production (Katuwal & Bohara, 2009) and analyse the implications of biogas and electricity-based cooking on energy use and greenhouse gas emissions (Pradhan et al., 2019).

The increasing recognition of the advantages offered by Geographical Information System (GIS)-based spatial mapping tools is evident. This methodology facilitates the optimal planning and implementation of bioenergy production facilities by efficiently acquiring crucial geospatial data regarding feedstock distribution. (Lovrak et al., 2020) exemplified this by leveraging GIS to evaluate the potential for biogas production from agricultural residues and municipal waste in Croatia. Moreover, similar methodologies have been implemented in Europe to appraise the spatial distribution of biogas potential derived from farm manure in livestock and poultry (Scarlat et al., 2018) and crop residues and waste (Einarsson & Persson, 2017). Assessing livestock manure as a viable feedstock for biogas generation, Ramos-Suárez et al. (Ramos-Suárez et al., 2019) analyzed to delineate biomass spatial distribution, electricity generation, and the reduction in greenhouse gas emissions resulting from substituting fossil fuels with biogas. Similarly, studies carried out in Argentina (Venier & Yabar, 2017), Pakistan (Khan et al., 2024), and Vietnam (Dao et al., 2020) have examined the biogas potential sourced from livestock manure through spatial analyses. While multiple studies have comprehensively investigated biogas potential using GIS approaches in other countries, there is a notable lack of similar studies in Nepal. The efficacy and in-depth insights of

GIS-based analysis studies in Nepal could significantly contribute to understanding and harnessing the country's waste biomass potential for sustainable bioenergy production. The absence of such a study emphasizes the significance of conducting similar studies within Nepal to capitalize on its waste biomass resources adequately.

Our study aims to fill the above-highlighted research gaps in understanding Nepal's spatial distribution of biogas production potential and its multiple benefits. We estimate the potential at the district level from available waste biomass (i.e., livestock manure, agricultural residues, and municipal solid waste) for 2021. Our benefits analysis estimates the replacement potential of LPG and chemical fertilisers by utilizing biogas and digestate, including reducing CO_2 and air pollutants emissions. We also evaluate the potential of biogas for bio-CNG and electricity production as part of the benefits. Our findings are valuable for municipalities, policymakers, and other stakeholders in promoting and developing policies to tap the biogas production potential, including its multiple benefits.

2. Material and Methods

We investigate the biogas production potential of waste biomass from livestock manure, agricultural residues, and municipal solid waste (MSW). Our study determines the availability of waste biomass at a district level by using the data on livestock, crop production, and OFMSW. Below, we elaborate on the data and method used for our study.

2.1 Data collection

Our study compiles data from multiple sources to investigate the biogas production potential (see Table S1-S4). Mainly, we estimate the quantities of manure and agricultural residues available for biogas generation using national agricultural, livestock, and population statistics at the district level. We obtain the livestock population and crop production data from the Ministry of Agriculture and Livestock Development (MoALD) (MoALD, 2022a, 2022b). Our study mainly focuses on manure from cattle, buffalo, sheep, goats, pigs, and poultry because they represent more than 99% of Nepal’s livestock (MoALD, 2022a).

For agricultural residues, we consider paddy, maize, wheat, and barley, which represent 44% of the total crop production in Nepal. Among the selected crops, paddy alone has a share of 23% of the total crop production in Nepal (MoALD, 2022b). We use the Central Bureau of Statistics (CBS) to retrieve information on the population of Nepal (CBS, 2022a). To calculate waste biomass, we compile data on manure produced by different livestock, and the residue-to-product ratio for crops (RPR), total solids (TS), volatile solids (VS), and biogas yield of different feedstock were taken from the scientific literature (Asian Development Bank, 2013; CBS, 2022b; Deublein & Steinhauser, 2011; Dinuccio et al., 2010; Kumar & Verma, 2021; Li et al., 2013; Lohani, Dhungana, et al., 2021; Lohani, Keitsch, et al., 2021; Vögeli et al., 2014). TS accounts for the total amount of solids present in a sample, whereas VS denotes the portion of organic solids in TS that can be utilised to produce biogas. Values for manure yield per livestock (kg day^{-1}), TS, VS, and biogas yield from different types of livestock manure are given in Table S1.

2.2 Estimation of Biogas Production Potential

Below, we describe the method used to estimate the biogas production potential from livestock manure, agricultural residues, and municipal solid waste.

2.2.1 Livestock manure

We first estimate the quantities of manure available from each livestock type at the district level based on its population data. See Equation (1), where *l* is the livestock type, and *d* is a district. However, the total manure cannot be collected due to practical issues, including livestock shed design and improper manure collection management. Therefore, our study considers a collection efficiency of 60% (Afotey & Sarpong, 2023). Afterward, we estimate the biogas production potential from livestock manure based on TS, VS, and biogas yield from Table 1 and using Equation (2) (Scarlat et al., 2018).

$$Total\ Manure_{l,d} = Total\ number\ of\ livestocks_{l,d} \times Manure_{l,d} \times collection\ efficiency \quad (1)$$

$$Biogas\ production\ potential = \sum_{l,d} Total\ Manure_{l,d} \times TS_l \times VS_l \times biogas\ yield_l \quad (2)$$

Additionally, we calculate livestock unit (LSU) at the district level using the livestock data (Table S2). Estimating LSU is crucial when choosing a location for potential biogas plants since those plants are more practical when they are close to a high concentration of LSU (Sliz-Szkliniarz & Vogt, 2012). The LSU is a reference unit that facilitates the aggregation of livestock from various species. The use of specific coefficients is established initially based on each animal's nutritional or feed requirement. The reference unit used to calculate LSU is the grazing equivalent of one adult dairy cow producing 3,000 kg of milk annually without additional concentrated foodstuffs (Eurostat, 2023).

2.2.2 Agricultural residues

We calculate the amount of agricultural residues using the crop production quantity produced in each district and the residue-to-product ratio (RPR) taken from Table S3 and Equation (3). In Equation (3), *c* is the crop type, and *d* is a district.

$$Agricultural\ residue_{c,d} = Crop\ production_{c,d} \times RPR_c \tag{3}$$

Biogas production potential from agricultural residues was calculated using Equation (4) (Bundhoo & Surroop, 2019). Table S3 provides the TS, VS, and biogas yield values for each crop type collected from the literature.

$$iogas\ production\ potential_{c,d} = Agricultural\ residue_{c,d} \times TS_c \times VS_c \times biogas\ yield \tag{4}$$

2.2.3 Municipal solid waste

The organic fraction of the municipal solid waste (OFMSW) from each district is estimated using Equation (5), where *d* is a district. The per capita MSW generation and organic fraction percentage were taken from Table S4.

$$\begin{aligned} &Organic\ fraction\ of\ municipal\ solid\ waste\ (OFMSW)_d \\ &= per\ capita\ municipal\ solid\ waste\ generation \times organic\ fraction\,\% \times population_d \end{aligned} \tag{5}$$

Biogas production potential from OFMSW was calculated using equation (6) (Dehkordi et al., 2020). TS, VS, and biogas yield were taken from the literature (Table S4).

$$Biogas\ production\ Potential_d = OFMSW_d \times TS\% \times VS\% \times biogas\ yield \tag{6}$$

2.3 Estimation of digestate potential

Besides biogas, digestate, a byproduct of AD, has an added value as organic fertiliser. Therefore, we also quantify digestate obtained while generating biogas from waste biomass using Equation (7) (Ngumah et al., 2013).

$$Digestate\ potential\ (dry) = (TS - VS) + ((1 - Biogas\ Yield\ \%) \times VS) \tag{7}$$

In Equation (7), biogas yield % is the quantity of VS converted to biogas. Around 60% of VS from livestock manure and agricultural residues gets converted to biogas (Ioannou-Ttofa et al., 2021; Kefalew & Lami, 2021). Similarly, 75% of VS from OFSMW gets converted to biogas (Deublein & Steinhauser, 2011).

The byproduct digestate could be used instead of chemical fertilisers. According to the 2018 biogas user survey, every household with a biogas plant used digestate as agricultural manure. The survey observed that with every kg of digestate applied, the consumption of urea (nitrogen-based fertiliser) and di-ammonium phosphate (DAP) reduced by 0.069 kg and 0.026 kg, respectively (AEPC, 2018).

2.4 Environmental analysis

Biogas can replace LPG and fuelwood as cooking fuel, lowering their negative environmental impacts, mainly CO_2 emissions and indoor air pollution. For estimating these replacement potentials, we take the calorific value of biogas as 22.7 MJ m^{-3} (Tian et al., 2017) and the CO_2 emission factor for LPG of 63 g MJ^{-1} (Lohani, Dhungana, et al., 2021). Equation (8) estimates CO_2 reduction by replacing LPG with biogas.

$$Avoided\ CO_2 = Biogas\ in\ MJ \times CO_2 emission\ factor\ for\ LPG \tag{8}$$

Similarly, using biogas for cooking can replace fuel wood, avoiding 4 g MJ^{-1} and 400 mg MJ^{-1} of air pollutants (CO and $PM_{2.5}$) (Weyant et al., 2019). Estimating avoided air pollutants can be done using Equation (9).

$$Avoided\ air\ pollutants = Biogas\ in\ MJ \times air\ pollutants\ emission\ factor \tag{9}$$

While biogas could reduce adverse environmental effects relating to cooking activities, biogas plants can produce some GHG emissions. Throughout the lifecycle of a biogas plant, the construction of the plant had comparatively minimal impact on the environment. This is mainly due to the long lifetime of such plants (Hijazi et al., 2016; Singh et al., 2020). However, during the operation of a biogas plant, some methane leakage is inevitable. Such fugitive leakages harm the environment (Singh et al., 2020). Up to 5% of the generated methane is assumed to contribute to fugitive leakages (Ayodele et al., 2018). Equation (10) calculates the fugitive emission from the biogas plant.

$$Fugitive\ emission = 5\% \ \times methane\ production \ \times density\ of\ methane \qquad (10)$$

We consider the density of methane to be 0.717 kg m^{-3} (Ayodele et al., 2018) and the methane production from biogas to be 60% (Gómez Montoya et al., 2016).

For comparison, fugitive emissions must be converted to CO_2 equivalent (CO_2eq). The global warming potential (GWP) of methane relative to CO_2 is 25 (Ayodele et al., 2018). Therefore, the carbon dioxide equivalent to methane (CO_2eq) can be calculated as given in Equation (11).

$$Fugitive\ emission\ (CO_{2eq}) = Fugitive\ emission\ \times GWP\ of\ CH_4\ relative\ to\ CO_2 \qquad (11)$$

We estimate the net GHG emissions from biogas as the difference between the emitted GHG due to fugitive leakage and the avoided GHG by replacing LPG with biogas, as shown in equation (12).

$$Net\ GHG\ emission = Avoided\ \ CO_2\ emission - \ Fugitive\ emission \qquad (12)$$

2.5 Estimation of LPG replacement and electricity production potential

A cylinder of LPG weighing 14.2 kg is equivalent to 29 m^3 biogas (Weyant et al., 2019). Therefore, we use this conversion unit to determine the number of comparable LPG cylinders that could be substituted from the potential biogas produced from waste biomass.

Biogas from livestock manure can be employed for electricity generation, considering biogas's 30% conversion efficiency to electricity (Saadabadi et al., 2019). The calorific value of biogas is taken as 22.7 MJ m^{-3}. The conversion factor of 3,600 is used to convert joule to watt-hour. The electricity production potential is based on the assumption that the biogas plant is operational for 7,500 hours per year (Venier & Yabar, 2017). Therefore, Equation (13) calculates the electricity production potential from livestock manure.

$$Electricity\ production\ potential\ (MW) = \frac{Biogas\ production\ Potential_d \times Calorific\ value\ of\ biogas \times Conversion\ efficiency}{3{,}600 \times 7{,}500} \quad (13)$$

2.6 Spatial analysis of biogas potential

We use the district-level estimates of the biogas production potential to calculate the number and size of the potential biogas plants in each district. Due to its ease of conversion to biogas without pretreatment, our study focuses on livestock manure as the feedstock to investigate the spatial distribution of potential biogas plants. Nevertheless, these plants could use agricultural waste or MSW as feedstock after segregation and treatment. For our current analysis, the availability of livestock manure at the district level was the sole factor in estimating the number of biogas plants in each district. The number of biogas plants in each district has been calculated based on the plant capacity (10 tons day^{-1}, 20 tons day^{-1}, 40 tons day^{-1}, and 60 tons day^{-1}) and available livestock manure. Although large-capacity biogas plants benefit from economies of scale (Ma et al., 2005), we have accounted for smaller-capacity plants because they could be distributed decentrally within a district.

3. Result

3.1 Biogas production potential

We estimate the total theoretical biogas production potential to be around 4,412 million m^3 year^{-1} (Table 1). Regarding feedstock, agricultural residues have the largest biogas potential, with an estimated 2,287 million m^3 year^{-1}, approximately 52% of the overall biogas production potential. Among the crops, the maximum biogas production is possible by utilising residues of paddy and maize, which account for 48% and 35% of the total biogas production capacity from agricultural residues (Table S5). It is because paddy constitutes 23% of the total crop production in Nepal. Livestock manure could also generate a considerable amount of biogas, i.e., 1,892 million m^3 year^{-1}, which accounts for 43% of the overall biogas production potential. The manure of buffaloes and cattle accounts for around 76% (approximately 38% each) of the total biogas production potential from livestock due to their large number and huge body size (Table S6). Because of Nepal's large population of goats and poultry, their manure could produce 10% and 9% of the biogas from livestock, respectively. Besides some large-scale commercial livestock farms, most agricultural households in Nepal also have a few livestock as an essential component of mixed farming systems. OFMSW contributes the least to potential biogas production, accounting for just 5% of overall biogas production potential, with a production capacity of 233 million m^3 $year^{-1}$.

Table 1: Biogas production potential from waste biomass.

Types of waste biomass	**Biogas Production Potential (million m^3 $year^{-1}$)**
Livestock manure	1892
Agricultural residues	2287
Organic fraction of municipal solid waste	233
Total	**4412**

The biogas production potential and the type of waste biomass vary across the districts of Nepal. Mainly, there is abundant biogas generation potential in the Terai region (see Figure S1 for Nepal's geographical map). For example, Jhapa, Morang, and Kailali are the top three districts in biogas production potential (Figure 1A). Kavrepalanchok, Ilam, Nuwakot, and Dhading are the Hilly districts of Nepal with a high potential for biogas production. The abundant biogas generation potential is associated mainly with livestock density and crop production.

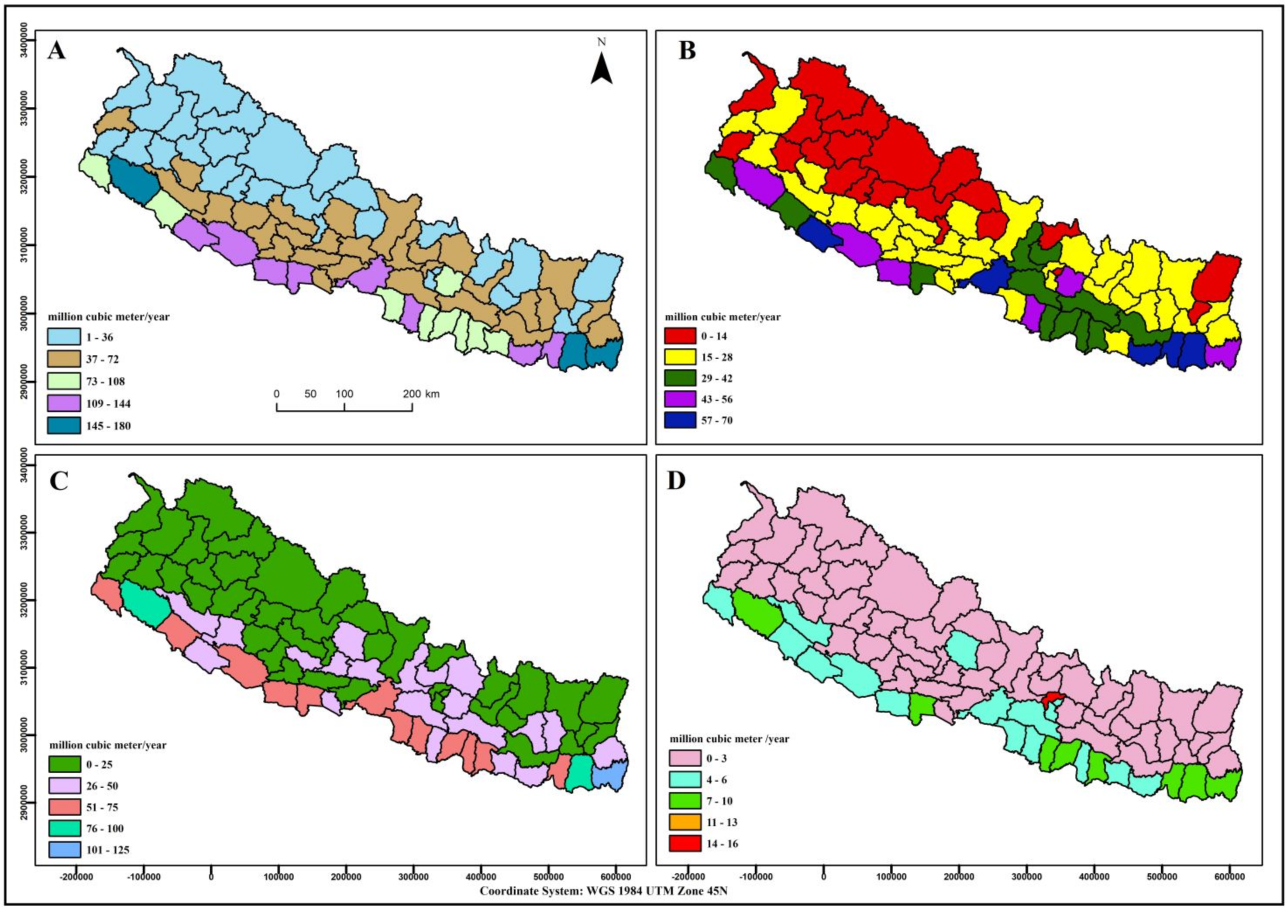

Figure 1 Spatial distribution of biogas production potential from waste biomass in Nepal: total potential (A), livestock manure (B), Agricultural residues (C), and the organic fraction of municipal solid waste (OFMSW) (D).

We find an enormous potential for biogas production from agricultural residues in Terai (Figure 1B). Terai is the hub for food production and agricultural residues in Nepal. Therefore, the maximum biogas production potential can be observed in this region. Jhapa, Morang, and Kailali are the districts with the most biogas potential from agricultural residues due to their extensive cultivated lands. These three are the only districts in Nepal with cereal harvest areas of over 100,000 hectares (MoALD, 2022b). Due to the enormous number of livestock, biogas production potential from manure is more feasible in the Hilly and Terai regions than in the Mountainous regions (Figure 1C). Among the districts, Morang, Sunsari, Saptari, Banke and Chitwan could produce more than 57 million m^3 $year^{-1}$ of biogas by utilising their livestock manure. These districts also have a relatively higher livestock density than others in Nepal (Figure S2).

Regarding the biogas production from OFMSW, Kathmandu, Morang, and Rupandehi have the highest potential, contributing 7%, 4%, and 4% of the total (Figure 1D). They are also the most populated districts in Nepal, having populations of 2,017,532, 1,147,186, and 1,118,975 in Kathmandu, Morang, and Rupendehi, respectively. In rural municipalities of Nepal, OFMSW is mainly fed to livestock or composted (CBS, 2022b). Thus, only the waste from urban municipalities can be used for biogas generation if adequately segregated.

3.2 Multiple Benefits of Biogas

Utilising biogas potential provides multiple benefits, including fuel and fertiliser. Nepal can replace around 153 million LPG cylinders annually using biogas from waste biomass (Table 2). This amount is about 4.6 times Nepal's current LPG consumption. The overall consumption of LPG in Nepal for 2021 was 33 million cylinders, of which 16.54 million cylinders were consumed in the residential sector (Water and Energy Commission Secretariat (WECS), 2022). With the substitution of the LPG cylinder for biogas, the country could save around NRs. 30 billion in the residential sector and NRs. 60 billion overall, given that a cylinder of LPG costs NRs. 1800 (NOC, 2023). It shows that biogas has enormous potential to reduce LPG imports, strengthen the national economy, green the energy sector, and sustainably satisfy the clean energy requirements. Moreover, if the produced biogas substitute LPG, avoided CO_2 emissions would be about 6 million tons year^{-1} (Table S7). However, biogas plants would also have fugitive emissions of around 2 million tons CO_2eq year^{-1}, resulting in a net CO_2 emission reduction potential of 6 million tons year^{-1}. Similarly, the produced biogas can substitute fuel wood, resulting in the air pollutant avoidance of CO of around 0.40 million tons year-^{1} and $PM_{2.5}$ of about 0.04 million tons year^{-1}.

Table 2 Liquefied petroleum gas (LPG) equivalent, digestate potential, and chemical fertilizer reduction potential, namely urea and Di-ammonium Phosphate (DAP), from adequate use of waste biomass, including the organic fraction of municipal solid waste (OFMSW)

Type of waste biomass	LPG equivalent (millions year^{-1})	Estimated digestate potential (million tons year^{-1})	Chemical fertiliser reduction (million tons year^{-1})	
			Urea	DAP
Livestock waste	65.26	3.98	0.28	0.10
Agricultural residues	79.86	4.86	0.34	0.13
OFMSW	8.02	0.27	0.02	0.01
Total	**153.14**	**9.10**	**0.63**	**0.24**

Regarding fertiliser, biogas plants can produce about 9 million tons year^{-1} of digestate (Table 2), which can be used for partial substitution of chemical fertiliser. Considering that a kilogram of digestate market price is at NRs. 22, the annual revenue from the sale of the digestate could be NRs. 200 billion. Applying the digestate could result in the yearly replacement of 0.63 million tons of urea and 0.24 million tons of DAP (Table 2). The annual sales of urea and DAP in Nepal for 2020/21 were 0.23 million tons and 0.14 million tons, respectively (MoALD, 2022b). Although the potential yearly production of digestate surpasses the urea and DAP sales by almost three times and two times, respectively, due to inadequate nutrients content, manure management practices, including a steady increase of digestate mix with chemical fertiliser for the partial substitution of chemical fertiliser is recommended (Al Seadi & Lukehurst, 2012). Although digestate can completely substitute the application of chemical fertilisers, the replacement would be a gradual process. Furthermore, some studies have shown that digestate coupled with chemical fertilisers improves soil quality and crop production (Rahaman et al., 2020; Tsachidou et al., 2019).

3.3 Spatial distribution of biogas potential

For utilising the biogas potential from livestock manure, Nepal needs to install 547, 234, 745, and 1206 plants with 10, 20, 40, and 60 tons day^{-1} capacity, respectively (Figure 2, top). The Terai region could have the highest number of biogas plants, mainly in the Jhapa, Morang, Sunsari, Sarlahi, and Saptari districts. These districts have a high concentration of LSU. In the Hilly region, Kavrepalanchok, Dhading, and Nuwakot are districts most suitable for developing biogas plants. Due to challenging transportation and difficulties with the centralised collection of livestock manure, these regions are appropriate for medium or small-scale biogas plants of 10 and 20 tons day^{-1}. In Figure 2 (top), the locations of different capacity plants are scattered based on feedstock availability in each district to reflect the potential numbers of different sizes of biogas plants in the district. Due to the unavailability of local-level data, we could not suggest the ideal location at the local level, accounting for feedstock availability, accessibility, and land use.

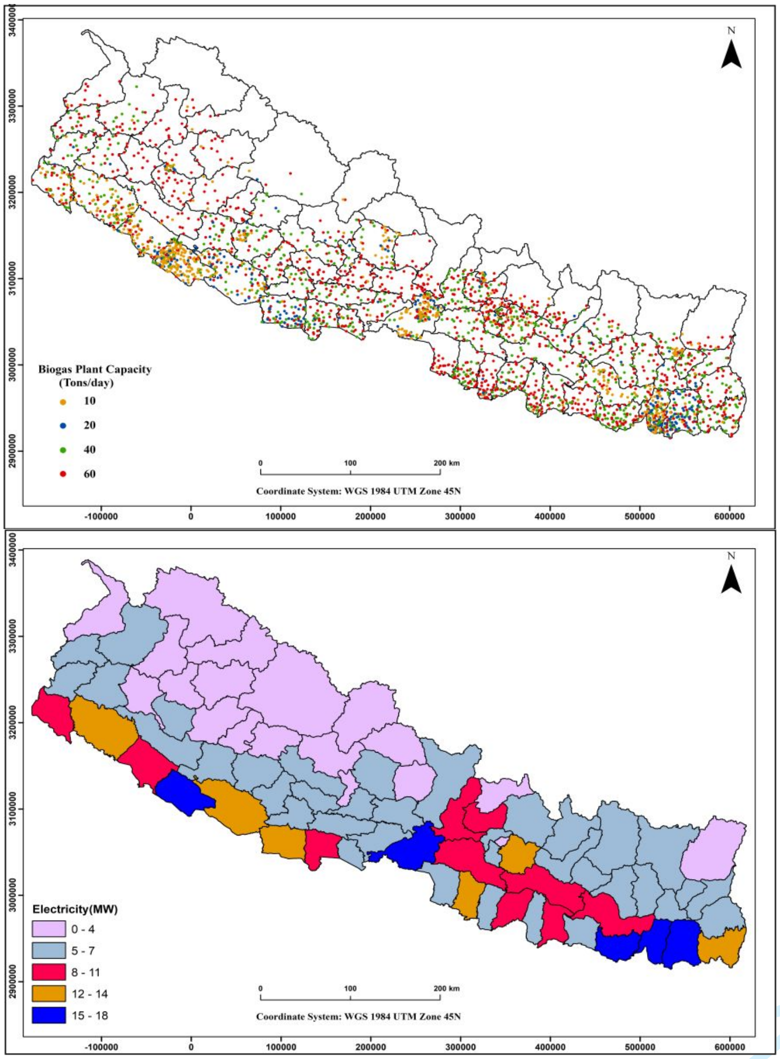

Figure 2 Spatial distribution of potential number and capacity of biogas plant (top) and total electricity production potential from biogas (bottom) in each district of Nepal

Nepal could produce 477 MW of electricity using livestock manure biogas (Figure 2, bottom). The Terai districts of Morang, Chitwan, Sunsari, Saptari, and Banke show promising potential for electricity production from biogas with a production potential of 18 MW, 17 MW, 16 MW, 15 MW, and 15 MW, respectively. Given the energy-intensive operations of biogas plants, some share of the generated electricity can be used for plant self-consumption. An appropriate substation for connecting to the national grid can be planned with the identification of potential districts for power generation. Furthermore, biogas plants may be situated next to industrial sites to utilise locally decentralised electricity distribution networks.

4. Discussion

Our study highlights the biogas production potential from waste biomass (livestock manure, agricultural residues, and municipal solid waste) in Nepal at the district level. Using the waste biomass, Nepal could produce biogas of 4,412 million m^3 $year^{-1}$ equivalent to 153 million LPG cylinders annually. This biogas could be used for cooking, transportation, or electricity generation with multiple benefits. These benefits include the reduction in greenhouse gas emissions and air pollution and the provision of organic fertilizers. Thus, biogas can contribute as an integral part of Nepal's clean energy mix. Our study brings several novelties and insights compared to the existing studies on renewable energy in Nepal.

First, we provide a spatial distribution of the biogas potential in Nepal, including the number of biogas plants with different installation capacities. Our analysis includes biogas potential from various waste biomass going beyond the existing studies, which mainly focus on livestock manure. Although the generation of biogas from agricultural residues is higher than that from livestock manure, several obstacles must be tackled to utilize this potential. Pretreatment is necessary for AD to improve biogas output because agricultural residues are rich in lignocellulosic components, which are difficult for microorganisms to decompose (Yu et al., 2019). Pretreatment is expensive and energy-intensive, raising biogas plants' investment and operating costs (Surendra et al., 2014). Moreover, feedstock including agricultural residue collection, supply-chain strategy and post installation operation and maintainace are also challenging. Nevertheless, combining the waste biomass, i.e., livestock manure, agricultural residues, and municipal solid waste, for co-digestion is a way to increase the biogas output. Doing so requires identifying suitable waste biomass within a specified location. Anaerobic co-digestion has been extensively used to overcome the disadvantage of mono-digestion and increase the feasibility of biogas plants due to improved biogas production (Lohani, Shakya, et al., 2021; Lohani̇, 2020). With the identification of the availability of suitable feedstock for co-digestion, stakeholders ranging from government agencies to the business sector could take the lead in developing and marketing appropriate technologies that can digest different feedstocks in Nepal.

Second, our estimates show that Nepal has enough livestock manure to supply feedstock for households and commercial biogas plants as planned in its SNDC to mitigate climate change (GoN, 2020). The Terai and Hilly regions are the most suitable areas for the plants because of their livestock density and climate, which are suitable for the AD of biomass. In Nepal, livestock manure has been used as a feedstock for household biogas plants. Promoting commercial biogas plants would require efficient collection systems for livestock manure, agricultural residues, and municipal solid waste. As discussed above, anaerobic co-digestion of biomass from these different sources would be an option for commercial biogas plants. Due to the economic scale, they could invest in feedstock pretreatment, maintaining mesophilic temperature, and regularly monitoring the AD process.

Third, our study highlights multiple benefits of utilising biogas potential besides providing clean energy. The produced biogas could be used for cooking by substituting LPG and other solid biomass and for transportation by replacing fossil fuel vehicles with CBG vehicles. Mainly, Nepal could save NRs. 260 billion annually by substituting LPG consumption with biogas and utilising digestate as fertiliser. Replacing LPG would also have a net greenhouse gas reduction effect of 4 million tons CO_2eq year^{-1}, which is around 30% of the annual CO_2 emissions from fossil fuels and industries of Nepal (Friedlingstein et al., 2022). It shows that biogas from waste biomass could be an essential strategy for Nepal toward a carbon-neutral development pathway, contributing to the decarbonisation of the energy sector (Lohani et al., 2023). Moreover, using biogas as clean cooking energy would reduce indoor air pollution, improving women's and children's health (Lee et al., 2023). Similarly, applying digestate as fertiliser would also help close yield gaps. Inadequate fertiliser application is a reason behind the current yield gaps in Nepal (Ladha et al., 2020; Pradhan et al., 2015).

Fourth, we introduce biogas as a potential source to ensure a stable electricity supply in Nepal regarding the energy mix. Hydropower is the dominant source of electricity in Nepal. However, seasonal water flow variation affects hydropower electricity production, especially from the run of river systems. So far, solar energy and storage systems are considered alternatives to provide an optimum energy mix for a stable supply of electricity in Nepal (Neupane et al., 2022). Adding to these alternatives, we highlighted the potential of producing 477 MW of electricity by using biogas from livestock manure. This potential would be even higher if all the waste biomass is considered. Using waste biomass for electricity production would help to dampen the fluctuation in electricity production due to seasonal variations of water flow and diurnal cycles of solar energy. The type of livestock manure directly influences biogas yield and the consequent electricity generation. Despite this variability, on average, a 60 TPD biogas plant has the potential to generate 0.3 MW of electricity. The strategic positioning of biogas plants of varying capacities within suitable areas would offer a decentralized electricity supply or CBG for transport and cooking purposes.

Our results also need to be taken very carefully considering their limitations. First, we are aware of the ambitious assumptions of the study. For example, centralised manure collection would be challenging due to the lack of such practices in Nepal (Adhikari & Adhikari, 2022). Similarly, the open burning of agricultural residues would hamper their use for producing biogas. Regarding municipal solid waste, the major obstacle to producing biogas is a lack of adequate infrastructure for collection and source segregation (CBS, 2021). Nevertheless, our study highlights the valorisation potential of waste biomass, which could be feasible by implementing appropriate policies and infrastructure. Second, this study uses national average data of MSW generation. MSW generation in cities and towns is more prominent than in villages. Moreover, OFMSW in villages is mainly used as a feedstock for cattle and piggeries. Third, this study considers constant biogas yield across the country regardless of the different climatic zones in the country. Biogas yield depends on the temperature, which varies with the climatic zone of the country. The digester temperature of the large-scale biogas plant is controlled to mesophilic temperature (37 ^{o}C) for optimum biogas production efficiency (Cheng et al., 2023). With varying climatic regions, the energy requirements for digester heating could be varied, while biogas production will be the same. However, the net energy output of the plant at varying weather conditions is of concern. Still, most of the recommended biogas plants are located in the country's southern region, the Terai belt, where a mean average temperature of 20-28 ^{o}C is relatively the same with negligible variation (Lohani, Dhungana, et al., 2021).

Moreover, using biogas as clean cooking energy for households offers enormous promise to advance various SDGs in synergy with clean and affordable energy for all (SDG 7). For instance, minimising household air pollution improves health-related targets (SDG 3), particularly for women and children (Lee et al., 2023). It also has strong synergies with climate action (SDG 13) by replacing fossil fuels in cooking and the transport sector. Using biogas for cooking would save time for women and children from avoiding firewood collection, including the possibility of doing other activities, e.g., education (SDG 4). It will also reduce deforestation and associated biodiversity loss (SDG 15). Digestate as fertiliser would increase crop productivity, improve food security (SDG 2), and increase household income. Because of these synergies, sustainable biogas based on adequate utilisation of waste biomass would also be an enabler for achieving the 2030

Agenda for Sustainable Development. Achieving SDGs is crucial to ensure the well-being of people and solve socioeconomic and environmental crises (Pradhan, 2023a) by leveraging synergies and tackling trade-offs. These synergies and trade-offs could vary within a country (Warchold et al., 2021), and data selection matters to understanding them (Warchold et al., 2022)

Our study assesses Nepal's waste biomass availability for biogas generation and identifies feasible sites for installing biogas plants. Building on these findings, further studies could venture into the techno-economic assessment of biogas plants at designated sites to ascertain their feasibility, providing valuable insights for informed decision-making and successful implementation. Reflections on the social acceptability of biogas for cleaner cooking transitions are also essential. Such research would significantly contribute to overcoming potential barriers and ensuring the long-term success of biogas initiatives in Nepal.

5. Conclusion and Policy Recommendations

Nepal could have produced four billion cubic meters of biogas using waste biomass in 2021. This sustainable biogas production capacity unlocks three clean energy possibilities: cooking, transportation, and electricity generation. Beyond its role as a fuel source, biogas offers significant environmental benefits by mitigating greenhouse gas emissions and air pollution while providing valuable organic fertilizer. Consequently, biogas is vital to Nepal's clean energy future. The biogas potential is mainly located in the Terai and Hilly regions of the country due to high livestock density and large cultivated areas. Utilising the biogas potential also has multiple benefits and synergies with several SDGs.

These findings are valuable for local municipalities, renewable energy companies, and policymakers for planning, designing, and implementing adequate strategies to accelerate the transition to renewable energy in Nepal. We enlist some actionable policy recommendations for sustainable biogas production in Nepal. First, Nepal needs to strengthen waste biomass collection and supply chains by investing in infrastructure and waste management systems and developing regional collection hubs and biomass aggregation centers. Second, it should promote anaerobic co-digestion, supporting research and development and providing financial and technical assistance. Third, the policymakers should leverage spatial analysis for strategic decision-making by using GIS-based mapping tools and incorporating biogas potential assessments into planning.

Fourth, Nepal needs to integrate biogas into diverse applications, e.g., biogas-powered cook stoves, appliances, and vehicles.

Conflict of interest statement

All authors declare no conflicts of interest related to the work in a manuscript.

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Supplementary Table

Table S1 Estimated physical parameters and biogas yield of various livestock manures, including total solids (TS) and volatile solids (VS). We obtained the data from Lohani and colleagues (Lohani, Dhungana, et al., 2021).

Livestock	Manure (kg head^{-1} day^{-1})	TS (%)	VS (%)	Biogas yield (m^3 kg^{-1} VS)
Cattle	12	15	80	0.31
Buffalo	14	20	75	0.31
Sheep	0.7	25	80	0.45
Goat	0.6	30	85	0.45
Pig	5	14	75	0.47
Poultry	0.12	25	75	0.45

Table S2 Livestock unit of various livestock types (*Eurostat*, 2023)

Livestock	Livestock Unit (LSU)
Cattle	1
Buffalo	1
Sheep	0.1
Goat	0.1
Pig	0.3
Poultry	0.01

Table S3 Estimated physical parameters and biogas yield of agricultural residues including total solids (TS) and volatile solids (VS). We obtained the data from multiple sources.

Crop	**Residue to Product Ratio (RPR)** (Kumar & Verma, 2021)	**TS (%)**	**VS (%)**	**Biogas yield ($m^3 kg^{-1}$ VS)** (Bundhoo & Surroop, 2019)	**References**
Paddy	1	88.7	91.9	0.24	(Dinuccio et al., 2010)
Maize	1.5	88.8	83.1	0.24	(Li et al., 2013)
Wheat	1	87.5	94	0.21	(Dieter Deublein & Angelika Steinhauser, 2011)
Barley	1.3	90.5	94.3	0.31	(Dinuccio et al., 2010)

Table S4 Estimated characterisation of municipal solid waste (MSW) in Nepal. We obtained the data from multiple sources.

Parameter	**Value**		**References**
Total Solids (TS)	30%		(Vögeli et al., 2014)
Volatile Solids (VS)	85%		
Biogas yield	0.45	$m^3 kg^{-1}$ VS	
MSW generation	0.32	kg $capita^{-1} day^{-1}$	(Asian Development Bank, 2013)
Organic fraction of MSW	60%		(Asian Development Bank, 2013; CBS, 2022b; Lohani, Keitsch, et al., 2021)

Table S5 Biogas production from different types of agricultural residues

S. N.	**Types of crops**	**Crop Production (million tones year $^{-1}$)**	**Agricultural residue (million tones year $^{-1}$)**	**Biogas production potential (million m^3 year $^{-1}$)**
1	Paddy	5.62	5.62	1,099.81
2	Maize	3.00	4.50	809.63
3	Wheat	2.13	2.13	367.43
4	Barley	0.03	0.04	10.19

Total	**10.78**	**12.28**	**2,287.07**

Table S6 Potential biogas production from livestock manure

Types of livestock	**No. of heads (millions)**	**Total manure (million m^3 year $^{-1}$)**	**Total manure including collection efficiency (million m^3 year $^{-1}$)**	**Biogas production potential (million m^3 year $^{-1}$)**
Cattle	7.47	32.70	19.62	718.20
Buffaloes	5.16	26.37	15.82	723.78
Sheep	0.79	0.20	0.12	11.00
Goat	13.44	2.94	1.77	190.77
Pigs	1.59	2.90	1.74	85.86
Poultry	73.42	3.22	1.93	162.80
Total	**101.87**	**68.33**	**41.00**	**1892.40**

Table S7 CO_2, CO and $PM_{2.5}$ emission avoidance from utilisation of waste biomass resources

Wastes biomass type	**CO_2 emission avoidance (million tons year $^{-1}$)**	**CO emission avoidance (million tons year^{-1})**	**$PM_{2.5}$ emission avoidance (million tons year $^{-1}$)**
Livestock Waste	2.71	0.17	0.02
Agricultural Residues	3.27	0.21	0.02
OFMSW	0.33	0.02	0.00
Total	**6.31**	**0.40**	**0.04**

Supplementary Figures

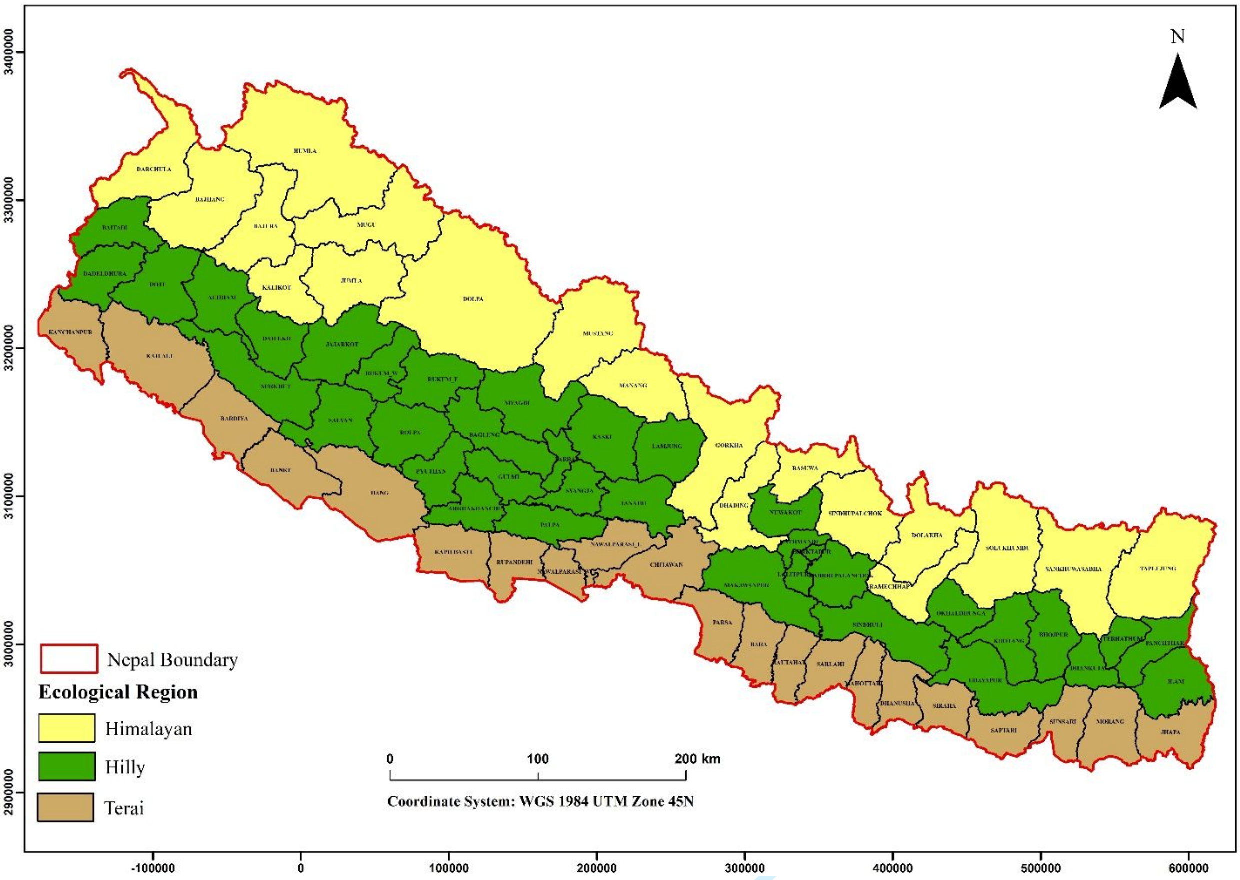

Figure S1 Geographical map of Nepal with political boundaries for districts and provinces

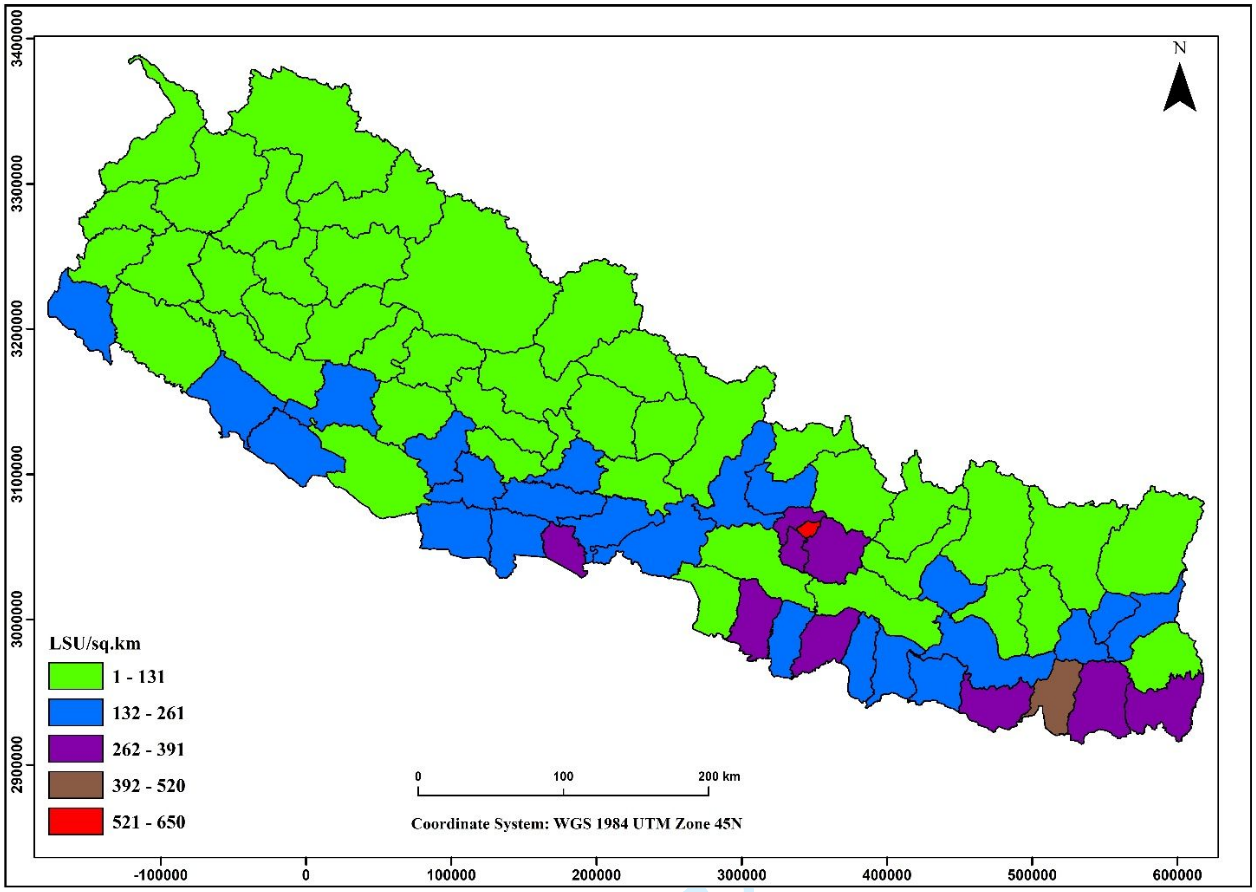

Figure S2 Spatial distribution of livestock unit (LSU) per Km^2. This distribution offers vital geographic details about the districts where potential biogas feedstock could be available.