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ORIGINAL ARTICLE

Possibilities and challenges for converting waste biomass into fuel, feed, and fertilizer in Nepal

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Abstract

Waste biomass is mainly used conventionally, without being converted into valuable products in developing countries, e.g., Nepal, mainly due to a lack of proper conversion knowledge, infrastructure, and resource data. We assessed the amount of biomass at sub-national (geography, province, and district) levels in Nepal to explore its conversion possibilities and challenges. Our assessment includes waste biomass such as agriculture crop residues, municipal waste, livestock, and human waste. We identified their current utilization practices and discussed their conversion possibilities, focusing on fuel, feed, and fertilizers. We estimated that about 1.7–5.0 million tonnes (Mt) of pellet/briquette and biochar, 1.7–5.1 Mt of feed block, 129–387 million m^3 of biogas, and 0.6–1.9 Mt of fertilizer can be produced in Nepal. The conversion of the waste biomass into valuable products can have significant environmental and economic benefits. Our findings can help authorities formulate appropriate policies and entrepreneurs to develop business plans for proper biomass utilization in Nepal at national and subnational levels.

Keywords Waste biomass · Biomass utilization · Biomass availability · Biomass conversion · Nepal

Introduction

Waste biomass is generated from different sources, such as forestry residue, agriculture crop residue (ACR), municipal organic waste (MOW), and livestock waste. The improper management of such residue and waste negatively impacts the overall biodiversity, a growing concern worldwide. For example, the poor handling and management of municipal solid waste (MSW), mainly generated from the urban sector, pollutes the surroundings (Gautam et al. 2024) and impacts overall biodiversity, including human health. Its management is one of the significant challenges for the concerned authorities, as it needs resources (Ejaz et al. 2010). MSW is being dumped and burned openly in Nepal (Pokhrel and Viraraghavan 2005). MSW comprises more than half of organic waste in developing countries (Kaza et al. 2018).

Similarly, open burning of crop residues, especially paddy straw, is practiced in Nepal, resulting in air pollution (Ravindra et al. 2019; Sadavarte et al. 2019). This

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practice is particularly prominent in Terai, where combined harvesters are employed, as they scatter straw across the fields, making collection impractical. Farmers often burn the straw as they find it economically unviable to collect and meet the next crop's cropping season. Livestock manures generate methane during decomposition (Pradhan and Kropp 2020), contributing to global warming. However, this gas could be trapped and utilized as energy using anaerobic digestion technology (Abbasi and Abbasi 2012).

Also, improper management of human waste, i.e., urine and feces, pollutes the soil and groundwater, affecting human health (Prajapati et al. 2021). Although the country has declared itself free from open defecation, dumping raw sewage and septic tank waste into rivers is common in Nepal (Pantha et al. 2021). Due to the lack of proper conversion knowledge and technology and the unavailability of status data, the waste biomass is improperly managed or conventionally used in many developing countries. The conventional use of waste biomass is less efficient, hazardous to the environment, and does not generate the economy. For example, using dry dung cake instead of biogas for cooking fuel is less efficient, degrades indoor air quality, and impacts human health. The lack of generation, consumption, and availability of data hinders policymaking and planning for the biomass-based industry.

To address the above-highlighted concerns, the waste biomass could be converted to produce high-value products that positively impact the environment and generate economy. The production of food, fuel, and other industrial products using bio-based materials is a new bioeconomy strategy for global sustainability (Peters et al. 2023). The sustainable and optimal use of available waste biomass is linked with low waste generation, and the conversion of waste to valuable products creates an additional economy, also termed circular bioeconomy (Corona et al. 2019). However, generating an economy through the available waste biomass utilization is still nascent and has gotten little attention in developing countries like Nepal. As the first step, promoting a waste-based industry requires quantifying the potential and current consumption at a sub-national level. So far, studies have estimated subnational-level potential and discussed the conversion possibility to valuable product pathways in a few developing countries, e.g., India (Hiloidhari et al. 2014), Uganda (Okello et al. 2013), and Romania (Scarlat et al. 2011). However, an estimate of waste biomass potential at the sub-national level and exploring its conversion pathways are missing for Nepal. Sub-national, here, represents the administrative and ecological regions of the country. Our study covers 77 districts, 7 provinces, and 3 geographies of Nepal based on its current administrative division. Although a recently published study (Lohani et al. 2024) has estimated the spatial data, it has focused only on the biogas generation potential.

In Nepal, the waste biomass is conventionally used mostly as fuel for cooking, feed for livestock, fertilizers, and housing materials. The country's primary energy supply is dominated by firewood from forests, ACR, and cattle dung cake, i.e., ≈67% of the total energy supply (≈633 Petajoules) in the fiscal year (FY) 2021/22 (MOF 2024). Similarly, ACR, especially straw and husk, is the primary source of cattle feed, and cattle dung is used as fertilizer (Poudel et al. 2019; Upreti and Shrestha 2006). Besides, cattle dung is also used to produce biogas in the country. Toilets are also connected to biogas plants in some houses (Gautam et al. 2009). In FY 2020/21 alone, about 3975 biogas plants were installed in Nepal (MOF 2024). It shows that the waste biomass is being utilized in modern ways, e.g., producing biogas; however, the majority is still untapped and is conventionally used or managed poorly. The proper utilization of such waste biomass needs quantification at the subnational level, which will help the development of innovative industries for sustainable development (Luo et al. 2024), such as by enhancing the local economy and jobs and increasing the share of renewable energy.

To fill the above-highlighted gaps, we have estimated the theoretical potential of the waste biomass in Nepal at the sub-national level: mainly agriculture crop residues, municipal organic waste, livestock dung, fowl litter, and human excreta. Considering geography and type of municipalities, we have calculated the available biomass for conversion to valuable products and quantified the production potential, specifically focusing on fuel, feed, and fertilizers. In addition, we have discussed the challenges of biomass conversion and highlighted the policy implications of our study to foster a biomass waste-based economy that contributes to sustainable development.

Methodology

Our study considered ACR, MOW, livestock waste, fowl litter, and human excreta and termed "waste biomass" to represent such residue and waste throughout the manuscript. We calculated the theoretical potential at the district level and aggregated it for the provincial, geography, and national estimates. The geography level categorizes districts into Terai, hills, and mountains (Table S1). Further, we considered the geography and type of municipalities to estimate available waste biomass conversion to valuable products. We quantified the production potential by suitability analysis, focusing on fuel, feed, and fertilizer. The current waste biomass utilization has been discussed based on the available literature and the economy survey report published by the Ministry of Finance (MOF 2024). Similarly, we assessed the literature to discuss the possibilities and challenges of converting available waste biomass to valuable products in Nepal and its policy implications.

Estimation of agricultural crop residues

We estimated ACR based on crop production data for the FY 2019/20 (MOAD 2021) and the respective value of the residue product ratio (RPR) (Table S2); see Eq. 1. We considered only data from a year on crop production as there has not been much variation in agriculture crops and production in Nepal in recent years (Table S3). To estimate ACR, we considered the major crops: cereals, cash crops, and pulses. Cereals include paddy, maize, millet, wheat, barley, and buckwheat, and cash crops consist of oilseeds, potatoes, and sugarcane.

$$Q_{ACR} = \sum_{i=1}^{77} \sum_{j=1}^{n} (CP_j \times RPR_{j,k}) \tag{1}$$

In Eq. 1, Q_{ACR} is the total quantity of ACR, i is the number of districts, n is crop types, CP_j is the annual production of crop j, and $RPR_{j,k}$ is the RPR of the respective crop j, and k is the type of residue (see Table S2 for details).

Estimation of municipal organic waste

We estimated the organic fraction of MSW, i.e., municipal organic waste (MOW), based on the population data of each municipality (CBS 2022), using Eq. 2. Solid waste generation by municipalities is obtained from the reports by the Asian Development Bank (ADB) (ADB 2013) and the Solid Waste Management Technical Support Center (SWMTSC) (Pathak 2017). The ADB report covers all 58 municipalities before adopting the federal government in Nepal (ADB 2013). The SWMTSC covers 60 new municipalities formed after adopting federalism with populations of less than 100,000 (Pathak 2017). In Nepal, only Kathmandu Metropolitan City has a population higher than 500,000. Most sub-metropolitan cities have a population between 100,000 and 500,000. The new federal system also introduced rural municipalities, most of which have populations of less than 25,000. To estimate the MSW, we first classified municipalities according to population size into five categories. We considered a weighted average value (gm/capita) to estimate MSW generation in each municipality (Table S4). A study conducted in 58 municipalities of Nepal, having a population of 4,523,820, found that 56% organic waste percentage in MSW (ADB 2013), while another study in 60 municipalities having a total population of 2,291,965 reported 61% (Pathak 2017). Therefore, we used the average weighted value of 57.86% while estimating the MOW.

$$Q_{MOW} = \sum_{i=1}^{77} \sum_{j=1}^{n} (N_j \times MT_i \times PCWG_j \times MOW_{\%}) \tag{2}$$

In Eq. 2, Q_{MOW} is the quantity of MOW, i is the district number, j is the number of municipalities in the i^{th} district, N_j is the population of the respective j^{th} municipality, MT_j is the type of municipality, which is done based on the population size, $PCWG_j$ is the per capita waste generation in j^{th} municipality, and $MOW_{\%}$ is the organic waste%, which is taken 57.86% for all municipalities.

Estimation of livestock, fowl, and human waste

We estimated the livestock, including fowl and human (LFH) waste, based on livestock and fowl population data from agriculture statistics (MOAD 2021) and human population from the census report of 2021 (CBS 2022), using Eq. 3. Per-head waste generation from LFH was taken from the literature (see Table S5 for details). We calculated the total LFH waste by multiplying population data with per-head waste (Eq. 3).

$$Q_{LFH} = \sum_{i=1}^{77} \sum_{j=1}^{n} (P_j \times PHWG_j) \tag{3}$$

In Eq. 3, Q_{LFH} is the quantity of waste from livestock, fowl, and humans; i is the number of districts; P_i is the district-wise population of livestock, fowl, or humans; j is types (livestock, fowl, and human); and $PHWG_j$ is the per head waste generation of respective j, i.e., livestock, fowl, and humans.

Estimation of fuel, feed, and fertilizer potential

Based on the existing literature, it is challenging to quantify the current utilization and surplus amount. Therefore, in this study, we have estimated the biomass availability for the conversion considering the country's geography for ACR, livestock, fowl, and humans, as well as the types of municipalities for MOW (Table S4). Due to geography constraints, poor infrastructure (e.g., road), and agriculture practices (including land use), we considered only 10% of the total theoretical waste biomass available for producing fuel, feed, and fertilizer in the mountain region except for human waste. Human waste is considered non-availability in the mountain region as our study has discussed its potential to produce biogas, and producing biogas in cold climates is not feasible. Similarly, we considered 20% from the hilly and 30% from the Terai region. This estimation is based on the study (Kafle et al. 2016). For MOW, we considered the collection efficiency of different types of municipalities: 72% from metropolitan, 43% sub-metropolitan, and 33% from municipalities as available potential. The data were generated based on the collection efficiency from the ADB report (ADB 2013). We did not consider rural municipalities as most municipalities have no waste collection facilities.

Based on the available biomass and suitable conversion options, we estimated the production potential of fuel (pellet/briquette and biogas), feed (densified total mixed ration), and fertilizer (biogas digestate/compost and biochar). Pellet/briquette, DTMR, and biochar are estimated considering moisture as it is, i.e., considering the same as biomass residue; however, fertilizer is calculated on the dry weight basis. The biogas generation potential is estimated considering dry matter (DM) content, fraction of volatile solid in DM, and biogas yield (Table S5).

Suitability and environmental impact assessment

We analyzed the suitability of converting available waste biomass to fuel, feed, and fertilizers based on the biomass and its types of residues (for crops). The analysis considered the geography (including terrain), the waste biomass properties (calorific value, nutritional value), the infrastructure needed, and the volume of waste available. The judgment was made based on the author's knowledge, considering the case of Nepal.

Similarly, to discuss the environmental impact, we estimated the avoided CO_2 emissions compared with the currently used fuel, such as coal in industries, which can be replaced by pellet/briquette, liquified petroleum gas (LPG), and firewood, which can be replaced by biogas. The avoided CO_2, CO, and PM2.5 were estimated considering the average calorific values for pellet/briquette, coal, and LPG of 14.9, 30.0, and 46.4 MJ/kg, respectively, and 22.7 MJ/m^3 of biogas (Bajracharya et al. 2017; Lohani et al. 2024; Verma et al. 2012; Weyant et al. 2019). The avoided CO_2 emissions estimated from biogas considering the LPG's CO_2 emission factor of 63 g/MJ (Lohani et al. 2024, 2021). Avoided CO_2 using pellet/briquette calculated considering the coal CO_2 emission factor of 90.91 g/MJ (EIA 2023). Similarly, avoided PM2.5 and CO of biogas compared with the firewood estimated considering 0.4 g/MJ and 4.0 g/MJ, respectively (Weyant et al. 2019). Further, based on the literature, we discussed the positive impacts of fertilizer, biochar, and densified total mixed rations.

Results

The potential of waste biomass varies countrywide in Nepal (Fig. 1a). It is higher in districts located in Terai and lower in the mountains than in other regions. At the provincial level, Koshi (21%) has the highest potential, followed by Bagmati (18%), and the least in Sudurpaschim (Fig. 1b). Geographically, the highest potential is estimated in the Terai, 49% of the total 89 million tonnes (Mt) (Table 1), followed by hills (43%), and just 10% in the mountain region. These differences are mainly due to the variation in land area, land-use practices, and climatic conditions. LFH waste accounts for 68% of the total generation potential, followed by ACR (30%) and municipal (2%).

Agricultural crop residues

Our estimates show Nepal produced ≈27 Mt of ACR in 2019/2020 (Table 1). Most of the ACR comes from paddy (43.72%), followed by Maize (24.10%) and wheat (14.30%) (Table S6). Rice is a staple food in Nepal, and Terai is suitable for growing paddy. Geographically, Teria is blessed with fertile land and favorable climatic conditions for growing crops. Thus, it has the highest ACR (59.35%), followed by Hills (35.59%) and just 5.06% in Mountain (Table 1).

At the provincial level, Madesh produces the most significant amount of ACR (≈6 Mt), i.e., 23.23% of the total, followed by Koshi (21.49%) (Table 1). The least amount of ACR is produced in Karnali (4.97%), followed by Sudurpaschim (8.92%). Madesh, widely referred to as the food basket of Nepal, is endowed with fertile terrain and a tropical savanna climate type with dry winters and hot summers. Additionally, it has more access to agricultural inputs such as fertilizers, pesticides, seeds, technology, and extension services. In contrast, the Karnali Province lies at high altitudes with sloppy terrain, and the climate and soil are also unfavorable for crop production.

The top three districts in terms of ACR are Jhapa (4.9%) followed by Sarlahi (4.4%) and Morang (4.1%) (Fig. S1). These three districts lie in the Terai and have a high share of arable land. Manang (0.02%) has the lowest ACR, followed by Mustang (0.03%) and Humla (0.06%). These three districts are in the high-altitude mountain region with harsh weather conditions for agriculture.

In Nepal, ACR is conventionally used as feed, fuel, fertilizer, and construction materials. For example, paddy straw is used for livestock feed and roofing for thatched houses. Paddy husk is considered livestock feed and fuel for residential and industrial purposes. According to the economic survey (MOF 2024), ACR contributed ≈3%, 18.80 of Petajoules (PJ) of Nepal's total energy consumption (≈633 PJ) in the fiscal year (FY) 2021/22. Taking the average heating value of ACR 14.90 MJ/kg (Kafle et al. 2016), we estimated that 1262 kt of ARC is currently used for energy purposes in Nepal, which is just about 5% of the total theoretical estimated ARC potential. Furthermore, ACR, e.g., straw, husk, bran, oilseed cake, and molasses, are major sources of livestock feed, providing around 50% of the total available daily livestock nutrition (Upreti and Shrestha 2006). Due to the unavailability of the feeding

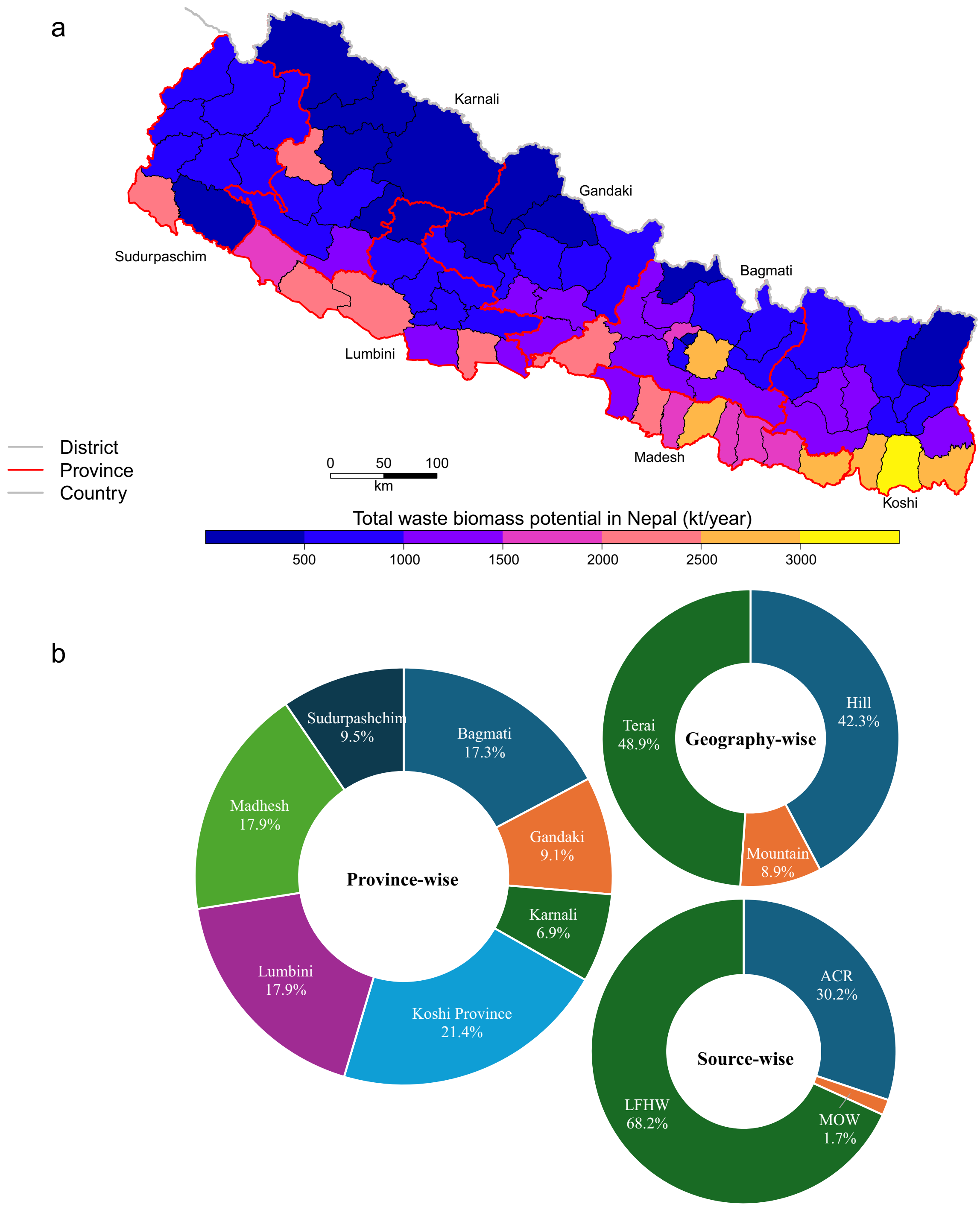

Fig. 1 Total waste biomass potential in Nepal **a** district-wise, **b** province, source, and geography-wise. It includes agriculture crop residues (ACR), municipal organic waste (MOW), and livestock, fowl, and human (LFH) wastes. The white zone on the map shows the unavailability of the data. kt/year: Kilo tonnes per year

pattern of livestock, it is challenging to quantify the current consumption of ACR as feed. Besides fuel and feed, ACR is also used for other purposes, e.g., animal bedding, mulching to increase soil organic carbon (Ghimire et al. 2008), building construction, and mushroom production. For example, a few studies investigated the benefits of mulching using ACR, mainly straw, in Nepal (Atreya et al. 2008; Gaire et al. 2013). However, they did not estimate

Table 1 Province and geography-wise waste biomass potential in Nepal. The Terai is estimated to have the highest agriculture crop residues (ACR), municipal organic waste (MOW), and livestock, fowl, and human (LFH) waste. At the provincial level, Madesh has the highest ACR, Bagmati has the highest MOW, and Koshi has the highest LFH. kt/year: Kilo tonnes per year

Provinces	Ecological belt	Potential (kt/year)			
		ACR	MOW	LFH	Total
Koshi	Terai	3215.0	166.7	5901.4	9283.1
	Hill	2111.0	62.7	5537.5	7711.2
	Mountain	423.9	14.4	1519.7	1957.9
	Total	5749.9	243.8	12,958.5	18,952.2
Madhesh	Terai	6214.3	285.7	9414.9	15,914.9
Bagmati	Terai	348.1	42.2	1715.3	2105.5
	Hill	2406.2	307.0	8633.0	11,346.2
	Mountain	460.9	18.0	1374.5	1853.4
	Total	3215.2	367.2	11,722.8	15,305.2
Gandaki	Terai	286.5	17.3	701.9	1005.8
	Hill	2088.6	111.9	4788.8	6989.3
	Mountain	12.0	0.7	78.4	91.1
	Total	2387.1	129.9	5569.1	8086.1
Lumbini	Terai	3771.1	202.9	7393.2	11,367.1
	Hill	1120.9	45.8	3352.6	4519.2
	Total	4892.0	248.6	10,745.7	15,886.4
Karnali	Hill	1131.6	54.1	2767.0	3952.7
	Mountain	199.2	15.6	1930.3	2145.1
	Total	1330.8	69.7	4697.3	6097.9
Sudurpaschim	Terai	2041.3	73.1	1578.8	3693.2
	Hill	663.1	30.9	2270.1	2964.1
	Mountain	256.5	16.9	1539.4	1812.8
	Total	2961.0	120.9	5388.3	8470.2
Total Nepal		26,750.2	1465.8	60,496.7	88,712.8

the total volume of ACR applied for mulching. Further, according to the population census (NSO 2023), about 3.9%, 0.26 out of 6.66 million houses in Nepal (2.79% in urban and 6.17% in rural) have thatched or straw roofs. Besides traditional uses, due to a lack of proper technologies and less value, open burning of ARC, especially paddy and wheat straw, is increasingly practiced in Nepal (Das et al. 2020; Pant 2015; Paudel et al. 2015).

Municipal organic waste

Our estimate highlights that Nepal generates about 6963 tonnes/day, i.e., 2.54 Mt/year of MSW, and 4016 tonnes/day, i.e., 1.47 Mt/year of MOW. Geographically, more than half (51.07%) of the MSW comes from Terai, about 43.69% on the hill, and just 5.24% on the mountain (Table 1). At the provincial level, Bagmati has the highest share (25.05%) of MOW because it consists of the highly populous capital city of Nepal. Madesh also generates a comparable amount (19.49%) of MOW, and Karnali contributes the least (4.76%). At the district level, we estimated the highest MOW in Kathmandu (440.08 t/day), followed by Morang (166.99 t/day), and the lowest in Manang (0.18 ton/day). For the uniformity of the result, MOW is plotted in kt/year (Fig. S2). MOW depends on population and urbanization. At the municipality level, Kathmandu Metropolitan City generates the highest amount of MOW (226.65 t/day), followed by Pokhara Metropolitan City (138.94 t/day) and Bharatpur Metropolitan City (72.28 t/day). Due to a large population, metropolitan cities generate a high volume of MOW, followed by sub-metropolitan, municipalities, and rural municipalities. Due to their number and population, the total MOW is higher in municipalities (49.35%), followed by rural municipalities (26.19%), metropolitan cities (14.86%), and sub-metropolitan cities (9.60%).

In Nepal, around 30% of households from urban municipalities practice composting to manage MOW (ADB 2013; Pathak 2017). So far, most rural municipalities have not set up waste collection and disposal mechanisms, resulting in waste management at the individual level, such as livestock feed and composting. Most urban municipalities, sub-metropolitan, and metropolitan cities have mechanisms and budgets for waste management (ADB 2013; Pathak 2017); in such municipalities, the collected waste can be converted to produce fuel and fertilizer. For example, kitchen waste is widely used for livestock feed and compost, but it has a limited application in producing biogas (Katuwal and Bohara 2009).

Livestock, fowl, and human waste

We estimated that Nepal generates about 60,497 kt/year of LFH waste, which consists of 54,517 kt/year from livestock, 3316 kt/year from fowl, and 2664 kt/year from humans. Cattle (49.93%) and buffalo (42.24%) contribute more than 90% of total livestock waste, followed by goat (4.37%), pig (2.85%), sheep (0.35%), and Yak/Nak/Chauri (0.25%). Geographically, about 45.21% of the total LFH waste is produced in the Terai, 44.14% in the hilly region, and 10.65% in the mountainous region. At the provincial level, LFH waste was estimated to be higher in Koshi Province (21.42%) and the lowest in Karnali Province (7.76%) (Table 1). At the district level, Morang generates the highest LFH waste (2265 kt/year), about 3.74% of the total, followed by Sunsari (3.40%) and Saptari (3.25%). We estimated the lowest LFH waste in Manang (0.04%), Mustang (0.09%), and Rasuwa (0.19%). Manang and Mustang are mountainous, cold-arid land unfavorable for raising livestock and fowl. There are also fewer human settlements (Fig. S3).

Livestock wastes are generally used as fertilizer, biogas feedstock, and dry dung cake as fuel for residential cooking and heating. In 2021/22, dry dung cake contributed about 10.8 PJ, about 1.7% of Nepal's total energy consumption (MOF 2024). Usually, cow dung, buffalo dung, and yak dung are used to make dry cakes in rural areas of Nepal. Dry dung cake usually has 10% moisture content and 9 MJ/kg calorific value. Accounting for these values, we estimated that about 1200 kt of dung at 10% or 10,800 kt of fresh dung, which has about 90% MC, is used for making dry dung cake in Nepal. Which is just about 20% of the estimated theoretical livestock waste. Further, as per the national population and housing census 2021 (NSO 2023), about 78,406 households used biogas for kitchen fuel, just about 1% of the total households in Nepal. Most of the biogas is used by households in the Terai region (77%), followed by hilly regions (20%). Cattle and buffalo dung are mainly used to generate biogas.

Waste biomass availability and conversion possibilities

Waste biomass has immense economic possibilities if properly utilized to produce fuel, feed, and fertilizer (Fig. S4). We have focused on the four prominent ways of converting it for generating economy: densified fuel (pellet and briquette), densified total mixed ration (DTMR) feed block, biogas cum fertilizer, and biochar. We estimated that about one-fourth of the total generation, i.e., 21,517 kt out of 88,713 kt, is available for producing valuable products. Out of 26,750 kt of ACR, about 6802 kt is estimated for availability. Similarly, 12,641 out of 54,517 kt livestock waste, 835 out of 3316 kt fowl litter, 630 out of 2664, and 609 out of 1466 kt MOW is estimated to be available for producing fuel, feed, and fertilizer. Based on the availability (Table 2) and possible conversion options (Table S7 and S8), we estimated that about 1667–5000 kt of pellet/briquette, 1701–5102 kt of DTMR, 129–387 million m^3 of biogas, 626–1878 kt of fertilizer, and 1667–5000 kt of biochar could be produced in Nepal.

Densified fuel (pellet and briquette) is a promising and profitable means of converting available biomass (Pirraglia et al. 2010; Trømborg et al. 2013). Solid biomass residue with higher calorific value and lower moisture contents is mainly recommended for briquette and pellet production. Therefore, in this study, we selected only ACR suitable for pellet/briquette production (Table S8). Suitability has also been discussed for the type of residues, such as paddy, which has straw, husk, and bran as residue. Bran is mostly used for oil production, so it is low-suited for pellet/briquette production. However, it is highly suitable for producing DTMR feed blocks. Suitability also depends on the geography; e.g., we do not consider ACR for pellet/briquette production in the mountain regions, considering the challenge of establishing such industries in the region. We estimated the production potential of pellet/briquette to be about 1190–3572 kt in Terai and 476–1428 kt in hilly regions. The study's finding is similar to that of the literature (Kafle et al. 2016), which has estimated that about 5610 kt of pellets can be produced from ACR.

In the Terai region, crop residue burning is increasingly practiced in Nepal (Pant 2015) to clear fields for the next crops. The use of combined harvesters mainly spreads the straw in the fields, which is challenging to collect, and due to not having economic value, farmers burn in the field, which results in air pollution and degrades the quality of the soil. Such ACR could be used for agro-pellet production, and cement factories and brick kilns could be Nepal's main fuel pellet market (Kafle et al. 2018, 2016). Currently, these industries depend on imported coal. Importing coal increases Nepal's trade deficits and contributes to greenhouse gas emissions. The environmental assessment estimated that replacing the coal using the pellet/briquette can avoid 2258–6773 kt of CO_2 emissions. The total CO_2 emissions from fuel burning were about 13,122 kt in 2021 (IEA 2024); the use of pellet/briquette instead of coal can lower the CO_2 emissions in the country by about 17–52%. Similarly, the estimated pellet/briquette has a total energy potential of about 25–75 PJ, which can meet about 4–12% of Nepal's total current energy consumption.

A densified total mixed ration (DTMR) feed block is an option to solve open field burning problems and shortage of feed, reduce transportation and storage costs, and increase livestock feed nutrients. DTMR feed block is produced by densifying straw, which reduces the bulk volume of straw to a ratio of about 3:1, reducing the fodder's transportation cost and saving storage space for other farm activities (Wali et al. 2012). For a country like Nepal, which does not have mass transportation (such as trains and waterways), the road transportation cost can be significantly reduced by producing and transporting DTMR feed blocks. DTMR is either paddy straw-based or wheat straw-based; paddy straw has lower nutritional value than wheat straw (Rauch et al. 2014). To add the nutritional value of DTMR, agro-industrial byproducts, e.g., bran/husk/hulls, oil-cake, molasses, grain, minerals, vitamins, and urea, are also added (Blümmel et al. 2014). Thus, DTMR is a mixture of nutritional additives and is a complete nutritional supplement for cattle. It also improves milk yield, composition, and digestibility (Sarker et al. 2019). Hence, DTMR is gaining popularity among livestock husbandry farms in the local area, which can be scaled up at the national level. The study has estimated that about 1701–5102 kt of DTMR feed block can be produced in Nepal, and most of its potential lies in the Terai region (1190–3572), followed by hill (476–1428), and less in the mountain region (34–101).

Another promising conversion technique is biogas and fertilizer production using biodegradable waste. LFH waste and MOW can mainly be used as raw materials for biogas and biofertilizer production. It is clean and eco-friendly and

Table 2 The available waste biomass has the potential to produce pellets/briquettes, DTMR, biogas, fertilizer, and biochar. The potential is estimated and shown in 25–75% of case scenarios

Sources of biomass	Geography/ Local level	Theoretical waste biomass (kt/year)	Collection efficiency/ Availability (%)	Available waste biomass (kt)	Potential (25–75% case)				
					Pellet/briquette (kt)[1]	DTMR (kt)[1]	Biogas (10^6 m^3)	Fertilizer (kt)[2]	Biochar (kt)[1]
ACR	Mountain	1352.5	10	135.2		33.8–101.4			
	Hill	9521.4	20	1904.3	476.1–1428.2	476.1–1428.2			476.1–1428.2
	Terai	15,876.3	30	4762.9	1190.7–3572.2	1190.7–3572.17			1190.7–3572.2
	Total	26,750.2		6802.4	1666.8–5000.4	1700.6–5101.8			1666.8–5000.4
Livestock	Mountain	6112.1	10	611.2				24.5–73.6	
	Hill	24,913.0	20	4982.6			42.0–126.0	199.5–598.5	
	Terai	23,491.4	30	7047.4			58.1–174.5	277.1–831.4	
	Total	54,516.5		12,641.2			100.1–300.5	501.1–1503.5	
Fowl	Mountain	133.9	10	13.4				1.3–3.8	
	Hill	1335.4	20	267.1			2.1–6.4	25.4–76.1	
	Terai	1847.0	30	554.1			4.5–13.4	52.6–157.9	
	Total	3316.3		834.6			6.6–19.8	79.3–237.8	
Human	Mountain	196.3	0	0.0					
	Hill	1100.5	20	220.1			1.6–4.9		
	Terai	1367.1	30	410.1			3.0–9.1		
	Total	2663.9		630.2			4.6–14.0		
OFMSW[3]	Metropolitan	383.8	72	276.4			7.9–23.8	20.7–62.2	
	Sub-metropolitan	217.9	43	93.7			2.7–8.1	7.0–21.1	
	Municipality	723.4	33	238.7			6.8–20.5	17.9–53.7	
	Rural municipality	140.8	0	0.0					
	Total	1465.9		608.8			17.4–52.4	45.7–137.0	
Total		**88,712.8**		**21,517.2**	**1666.8–5000.4**	**1700.6–5101.8**	**128.7–386.7**	**626.1–1878.3**	**1666.8–5000.4**

[1]Considering moisture as it is (same for raw biomass and product)

[2]Dry matter weight (zero moisture content)

[3]Total solid 30%, Voltaile solid (85%), Biogas yield (0.45 m^3/kg VS)

can replace traditional fuel used in residential and commercial sectors. The Government of Nepal has promoted the residential, institutional, community, and commercial biogas plants by providing subsidies. The government is also promoting large-scale biogas plants as a tool for managing MOW and intends to replace conventional cooking fuel. In the last few years, many private companies, institutions, and hospitals have shown interest in building large-scale commercial biogas cum fertilizer plants (Lohani et al. 2021). This study has estimated the potential of fertilizer production using livestock and fowl. The estimation shows that fertilizer production from livestock is highest in the Terai region (295–885 kt), followed by the hilly region (194–581 kt) and the Himalayan region (22–65 kt). However, fowl contribute only a small extent to fertilizer production, mainly from the Terai region (51–156 kt), followed by the hilly region (27–80 kt) and the Himalayan region (1–3 kt).

We considered that human waste can only be used for biogas production, as farmers and consumers do not accept human waste as fertilizer, and it is currently not practiced. The total biogas production was estimated at about 129–387 million m^3, out of which 100–301 million m^3 from livestock, 7–20 million m^3 from fowl, 5–14 million m^3 from human waste, and 17–52 million m^3 from municipal solid waste. This shows that the Terai region and rural municipalities have a higher potential for biogas production. Using biogas to replace LPG and fuelwood, Nepal can potentially avoid 184–553 kt of CO2 emission, 12–35 kt of CO emission, and 1–4 kt of air pollutant ($PM_{2.5}$). The estimated biogas has an energy generation potential of 3–9 PJ.

Biochar is another promising technique to valorize available waste, which is produced by thermal decomposition (pyrolysis) (Paudel et al. 2024); ACR can be used to produce it. Biochar is added to the soil to improve soil health and ultimately to increase agricultural productivity by increasing the soil fertility of acidic soils. It is also used as fuel because it burns without producing smoke. Similarly, the biochar-based medium can be used as a low-cost medium in the fermentation industry as it provides pH buffering capacity and nutrients, such as trace metal (Sun et al. 2020). Because of its benefits to soil and the environment, numerous pieces of research are conducted worldwide in this field. Its research is also booming in Nepal, mainly on the benefits of biochar application to increase agricultural production (Pandit et al. 2018; Schmidt et al. 2017). A study conducting 3 years of biochar field trials in Nepal found a significant increase in maize and mustard productivity (Pandit et al. 2018). This study estimated Nepal's biochar potential from the ACR at around 1667–5000 kt: 1190–3572 kt in Terai and 476–1428 kt in hill.

Discussions

We quantified the waste biomass potential from Nepal's agriculture, municipal, livestock, fowl, and humans at the sub-national level: district, province, and geography. Overall, the highest potential is estimated in Koshi province-wise, hill geography-wise, and Jhapa district-wise. Our study also found variations across the country due to sources, land-use practices, and climatic conditions. We further estimated the availability for commercial conversion purposes and the generation potential of pellet/briquette, DTMR feed block, biogas, fertilizer, and biochar. In this section, we discussed the challenges of producing fuel, feed, and fertilizers from the available waste biomass, along with this study's policy implications and limitations.

Challenges of producing fuel, feed, and fertilizer

We focused the discussion on seven key challenges hindering the waste biomass conversion into high-value products, such as fuel, feed, and fertilizer. These challenges are elaborated below.

The first challenge is the lack of location-specific data. Our study has quantified the generation potential at the subnational level (district, province, and geography). However, we must still quantify the consumption and surplus data required to plan waste-based industries properly. For example, we estimated about 62 MT of the waste biomass generation potential from the LFH and about 23 kt of such waste biomass in the Manang district; designing a fuel and fertilizer industry in the district needs current consumption and surplus data as well for the sustainability of the project. Similarly, the study has also accounted for the MOW potential in rural municipalities; however, many municipalities have no waste collection facilities. So, a location-specific plan is recommended; for example, the Jhapa and Morang districts have the highest ACR from Paddy, and the DTMR block plants could be established in these districts, which reduces the transportation cost of the raw resources. Similarly, after Jhapa district, Illam and Bhojpur have the highest potential for maize residue production. Industries should focus on maize residues in such districts to convert them into high-value products. Wheat is mainly produced in the Terai region, while barley and buckwheat are grown in hilly and mountainous regions, so according to plan is needed.

Another challenge is the infrastructure, as the country's transportation infrastructures and networks (Isha Gharti 2022) have made it difficult to properly reach and transport resources from the source to the plant. Nepal has no bulk transportation systems, such as trains and waterways. Only road-based vehicles, e.g., trucks and tractors, are common means of transportation, which are costlier and can carry limited quantities only.

The third challenge is the topography and terrain of the country. More than half of the waste is estimated in the hill and mountain, 42.25% and 8.86%, respectively. Nepal's sloppy terrain makes reaching all the sites and harvesting, collecting, and transporting the waste biomass difficult. Considering the challenges, the study (Kafle et al. 2016) has taken only 10, 20, and 30% of the total available ACR potential in the Mountain, Hill, and Terai regions, respectively, for agro-pellet production, which is also adopted for this study to estimate the availability for producing fuel, feed, and fertilizer.

Another challenge is human resources and technology, as the country also lacks competent human resources for developing strategies and execution (ILO 2016). In addition, the general public's poor level of education and awareness regarding effective management of the waste biomass and the consequences of improper handling (such as burning and open dumping) (ADB 2013) have made it challenging to manage and convert the waste to valuable products effectively. Similarly, the waste-based industry needs advanced and sustainable technologies, but the country lacks such technologies; it ranked 111 in the global innovation index in 2021 (WIPO 2021).

The fifth challenge is the investment and market, as the waste-based industry needs high upfront cost/investment. But, being a lower middle-income country, the country ranks 108th in the global startup ecosystems index (StartupBlink 2023), and the uncertainty has hindered the country's establishment of the waste-based industries.

Another challenge is that the execution of the waste biomass management regulations and policies is insufficient despite laws (Shrestha 2019), which resulted in poor management and hindered the promotion of the waste-based industry.

The seventh challenge is the poor intersectoral coordination among different tiers of government: municipal, provincial, and federal. The poor intersectoral coordination mechanism (Bhele 2019) and insufficient budget have hindered the enabling environment for generating the economy utilizing the waste biomass. The country has fewer priorities for allocating a budget for research and development

(Acharya et al. 2021), which is necessary for developing effective waste management and conversion technologies.

Policy implications

Our research offers fresh perspectives on Nepal's potential to produce fuel, feed, and fertilizer utilizing the waste biomass at the subnational level. Considering our findings, several strategies and policies could be developed to support biomass utilization in Nepal.

First, our study quantifies the available waste biomass at the subnational level in Nepal, most of which is utilized in conventional ways, and it is scattered all over the country. The waste biomass sources also vary location-wise; for example, a higher amount of municipal waste is estimated in the Kathmandu district, and a higher ACR is estimated for the Jhapa district. Similarly, a higher ACR is estimated in the Terai region. Overall, the lowest potential is calculated for the Manang and Mustang districts; however, the Yak/Nak/Chauri waste is more substantial in these districts than in other districts. Therefore, the sub-national level data of the study could be helpful for the country to formulate plans, policies, and strategies for the proper utilization of resources.

Second, our study has discussed Nepal's current waste biomass management practices and how poor management degrades the environment and human health. For example, cattle dung is being used, especially in Terai, to make dry dung cake and use it for cooking fuel, degrading indoor air quality — impacting women and children, who spend most of their time in the kitchen. Similarly, poor municipal waste management by openly dumping and burning near water bodies and forests pollutes the surroundings. Similarly, due to not having economic value, farmers practice crop residue burning in the Terai region of Nepal, which can be reduced by establishing waste-based industries and providing schemes of monetary incentives with proper regulations. So, the comprehensive discussion of the study could help formulate policies and regulations needed for appropriate management and utilization of the available resources. Further, it helps develop regulations for reducing improper waste management practices, which helps to conserve the greener environment.

Third, the study has identified the enormous amount of the waste biomass potential at the subnational level, such as about 1313 kt/year ACR in the Jhapa district, 161 kt/year MOW in Kathmandu district, and 2265 kt/year LFH waste in Morang district. These resources could be used by establishing large-scale industries, such as pellet plants focusing on high calorific solid residue (ACR), large-scale biogas cum fertilizer plants focusing on MOW and LFH waste, and feed industries focusing on ACR. So, the study's findings could help formulate the policies to promote the waste-based industries in the country, which, on the one hand, solve the waste management problems and their associated environmental consequences. On the other hand, producing fuel, feed, and fertilizer could fill the need for national demand. Thermal-based power plants, especially brick kilns and cement industries, consume imported coal to meet their thermal energy demand, which fuel pellets can replace. Similarly, Nepalese farmers rely on chemical fertilizers to supply nutrients to the soil, which can be reduced by applying bio-fertilizers.

Fourth, based on secondary literature, our study has estimated the waste biomass generation potential at the subnational level; however, primary ground data, with collection efficiency, consumption pattern, and surplus, are vital for proper planning and policy development. Similarly, this study has not quantified the potential of economic generation and associated environmental impacts, which is most important for choosing the best conversion option. So, appropriate planning and policies to promote research are vital, which helps develop proper management and utilization strategies.

Limitations

Our study has a few limitations, which need to be accounted for when using our results. The first limitation relates to the data used. For example, the ACR is estimated based on the production and crop-residue ratio, taking only the value for each crop. However, it may vary with the variety of crops grown. Nevertheless, we have optimum use of the recent and relevant available data.

We evaluated the theoretical waste biomass resource potential at the subnational level, covered current biomass management and consumption practices, and estimated and quantified the generation focusing on fuel, feed, and fertilizers (FFF). However, quantifying potential revenue generation has yet to be evaluated, which is the second limitation of the study. However, the study has presented the data at the subnational level for Nepal, which would be helpful for future studies.

The third limitation of the study is that we have not investigated and mapped the waste biomass surplus and deficit zones at the subnational level. The subnational-level waste flow map (Sankey diagram) covering theoretical potential, techno-economically available potential, and quantity consumption practices is necessary for mapping surplus and deficit zones. That is the utmost for locating the waste-based industries. However, our study will create a discourse for developing proper biomass utilization strategies.

Conclusion

Waste biomass is mainly consumed conventionally in Nepal, although it can be used to produce fuel, feed, and fertilizer. We estimated a total of 89 Mt/year theoretical generation of the waste biomass in Nepal, of which 21 Mt/year is estimated to be available for producing fuel, feed, and fertilizer. Districts in Terai have higher potential than mountainous regions due to geography, land use, and land area variations. Considering the availability from 25–75%, we estimated that about 1.67–5.00, 1.70–5.10, and 0.63–1.88 Mt/year of pellet/briquette and biochar, DTMR, and fertilizer, respectively, and 128.7 and 386.7 million m^3 of biogas can be produced in Nepal. Densified biomass fuel (pellets and briquette), DTMR feed block, and biochar can mainly be produced from ACR. MOW, livestock, and fowl waste could be converted to biogas and fertilizer, and human waste can be converted to biogas. As biomass is scattered all over the country, it has numerous challenges, including a lack of location-specific availability, consumption, surplus data, infrastructures, investment, human resources, and challenging topography and terrain of the country.

Moreover, further study could explore the techno-economic and environmental feasibility of producing fuel, feed, and fertilizer from the waste biomass in Nepal, estimating the current use and surplus at the subnational level.

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Data Availability Most of the data are contained within the article. The raw data can be available on request from the corresponding author.

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