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Assessing greenhouse gas emissions and decarbonization potential of household biogas plant: Nepal's case study

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Abstract

Household biogas plants (HBPs) are widely promoted in developing countries like Nepal to decarbonize the cooking fuel sector, mitigating greenhouse gas (GHG) emissions associated with traditional, non-clean cooking fuels. However, their decarbonization potential mainly relies on the overall GHG emissions associated with HBP and the avoidable emissions to be substituted by the HBP, and there is a lack of systematic studies evaluating these emissions under Nepalese context. This study addresses this gap, probably for the first time in Nepal, by analysing GHG emissions associated with HBP, assessing their decarbonization potential under various operational conditions, and identifying opportunities to enhance the potential. Using a life cycle assessment (LCA) approach, we examined the decarbonization potential of HBPs and evaluated the impact of their operational uncertainties through sensitivity analysis. Our results indicate that HBPs could decarbonize the cooking fuel sector in Nepal by around 150,000 kilotons of CO_2 equivalent annually; however, GHG emissions from about two-third of HBPs exceeded avoidable emissions, hindering their overall decarbonization potential. To improve this potential, we recommend strategies such as effective operation and maintenance, efficient digestate utilization, and context (regional, socioeconomic etc.) specific intervention policies such as biogas yield enhancement through codigestion of locally available feedstock. These findings provide valuable insights for policymakers aiming to assess and enhance the

decarbonization potential of HBPs in Nepal and other parts of the developing countries under similar contexts.

Keywords: Household biogas plant, Life cycle assessment, Decarbonization, Digestate, Greenhouse gas emissions

Introduction

The Paris Agreement has set the ambitious goal of achieving net-zero emissions by 2045. Signatory countries must present a roadmap outlining measures to mitigate greenhouse gas (GHG) emissions (UNFCC, 2015a). The energy sector poses a significant challenge in realizing this goal, as around three-quarters of the total GHG emissions result globally from this sector only (International Energy Agency, 2023). Therefore, it is imperative to explore opportunities for GHG emission mitigation within the energy sector for effective decarbonization.

While the energy sector is the largest contributor to global GHG emissions, the sources and dynamics of these emissions differ considerably between developed and developing countries. Developed countries have made significant strides in decarbonizing their energy sectors through the adoption of renewables and enhanced energy efficiency policies, in contrast, the energy sector in developing countries still heavily relies on non-cleaner traditional fuel such as forest wood, crop residues, animal dung etc., and fossil fuels, resulting in slow progress toward decarbonization (Kabyanga et al., 2018). Particularly, the residential sector in these regions remains a major hurdle in this regard due to the heavy use of non-cleaner traditional fuels as primary cooking fuels. (D. Bhattarai et al., 2018; International Energy Agency, 2023). Therefore, developing countries like Nepal is now implementing specific action plans to mitigate GHG emissions based on their local energy mix scenarios (U. Bhattarai et al., 2024; Government of Nepal, 2021).

In Nepal, recent studies have estimated 60 million $MtCO_2$ emissions in 2019, which is projected to double by 2040 under a business-as-usual scenario. The energy sector alone has accounted for 54% of the CO_2 emissions in 2019 and around two-thirds of this energy is consumed by the residential sector, mainly for cooking and heating purposes(Government of Nepal, 2021). Within the residential sector, around 65% of Nepalese households rely on non-cleaner traditional fuels such as forest wood, cow dung, agroresidue etc., and 17% use fossil fuels for cooking (WECS Nepal, 2024), both of which contribute to significant GHG emissions causing environmental degradation and adverse health impact (Rosenthal et al., 2018). Hence, substituting traditional fuels and fossil fuels with cleaner forms of energy has been proposed as one of the strategies in Nepal to decarbonize the cooking sector. Nepal's commitment to achieving Sustainable Development Goal (SDG) 7 has further fuelled this initiative and emphasized providing cleaner energy for all (Rosenthal et al., 2018).

HBPs, which convert domestic waste like livestock manure, kitchen wastes and human excreta into biogas for cooking, have been identified as a promising solution for mitigating GHG emissions in Nepal (Gautam et al., 2009). They mitigate GHG emissions by preventing methane and nitrous oxide emissions from untreated waste and substituting traditional fuels with biogas. Moreover, the digestate produced as a by-product can be used as fertilizer, reducing the need for chemical fertilizers and their associated emissions (Feng et al., 2023). Further, Nepal has substantial potential for biogas production, with livestock manure alone capable of generating 3044 million cubic meters of biogas annually which is more than four times the country's current consumption of liquefied petroleum gas (LPG) cylinders (Lohani et al., 2021). This could significantly decarbonize the cooking fuel sector mitigating GHG emissions substituting non-cleaner cooking fuels. Besides these technical potential, state-sponsored regulatory body dealing with renewable energy, along with financial and technical support from development partners, have facilitated the widespread adoption of HBP throughout Nepal. Around half a million such plants have been installed (Adhikari & Adhikari, 2022; AEPC, 2023). Socioeconomic benefits and social well-being have also been improved in the communities where HBPs are promoted (Gautam et al., 2009; Pizarro-Loaiza et al., 2021). Despite these potential and opportunities, the environmental impact, particularly the GHG emissions associated with HBP in Nepal, remains highly unexplored. Therefore, decarbonization features of HBP may sometimes be under serious question mark in the absence of GHG emissions monitoring and mitigation during its operation and application (Roubík et al., 2020; Vu et al., 2015). As Nepal has proposed HBP as a strategy to decarbonize the cooking fuel sector, there is a pressing need to quantify the emissions mitigation potential of HBPs and assess their decarbonization potential to meet national target outlined in nationally determined contribution (Government of Nepal, 2021).

Although several HBP related studies have examined their sustainability from technical, socioeconomic, and institutional aspects in Nepal, limited such studies have been carried out to assess their environmental performance. Further these studies are implicit in nature (Cheng et al., 2014; Jha & Lohani, 2023; Lohani et al., 2022). In other words, these studies have not evaluated the emissions quantitatively, rather revealed a significant occurrence of fugitive emissions of biogas due to damaged pipelines, valves, and cooking stoves. Past research has also indicated that unutilized digestate could be a significant source of GHG emissions.

Besides these scientific studies, the annual biogas user survey is another provision to monitor emissions during HBP's operation. Still, this provision specifically applies to HBP registered under the clean development mechanism (CDM). Specific guidelines are available to select HBP sites and questionnaire to explore the environmental impact in terms of emissions during the survey. Although the guideline has advised to employ stratified random sampling techniques to select HBP sites, the survey does not include questionnaire aiming to estimate fugitive emissions or emissions from digestate (UNFCC, 2015b). Estimating these emissions requires a detailed field survey to assess the physical and operational condition of key HBP components, such as digester structure, pipelines, valves, and cooking stove performance. For example, fugitive emissions in HBP systems in developing countries are estimated ranging from 1% to 60% of total biogas production depending upon the technical condition of HBPs, as suggested by Bruun et al., 2014. Similarly, HBP user's digestate management practice such as frequency and quantity of digestate utilization can provide valuable data for the emissions associated with unutilized digestate. Therefore, survey based on the questionnaire exploring the above-mentioned parameters may be proved crucial, mainly in developing countries like Nepal, where national emissions inventory guideline associated with HBD is not available and it could be considered as a reference in the absence of actual emissions data or estimation methods (Ioannou-Ttofa et al., 2021).

Besides the above-mentioned limitations associated with current format of biogas user's survey, some limitations persist within the methodological framework to estimate carbon emission reduction (CER) potential of HBP which is needed prior to be registered under CDM. For example, two key sources of GHG emissions in HBPs need to be explored to assess the CER by HBP: first, the indirect emissions associated with input materials and services; and second, the direct emissions linked to fuel combustion throughout the life cycle of HBP (Roubík et al., 2020). However, the existing methodology considers direct emissions only. Further, it tends to focus primarily on CO_2 emissions only during estimation of CER, neglecting other potent GHGs like methane and nitrous oxide, which are associated with biogas leakage and unutilized digestate (Gold Standard Foundation, 2017). These gases have been shown to contribute significantly to overall GHG emissions (IPCC, 2006). Moreover, construction phase emissions have been overlooked however such emissions were found crucial in some cases (Supplementary Table S1). Similarly, the existing methodology primarily considers CER from substituting only forest wood with biogas. Although forest wood is the predominant cooking fuel in country, Nepal is promoting other clean cooking fuels like LPG and electric cooking through subsidies and favourable policy tools (Clean Cooking Alliance, 2022). Hence, it is essential to explore the decarbonization potential of HBPs considering substitution of cooking fuels other than forest wood too and it emphasizes on need to a more comprehensive emissions estimation methodology to assess GHG emissions across all phases of the HBP lifecycle. Such an approach would reveal opportunities for emission reductions and enhance the decarbonization potential of HBPs. Therefore, Life Cycle Assessment (LCA) is particularly valuable in this context, as it accounts for emissions throughout the entire lifecycle of the system, from the sourcing of construction materials to biogas production and the disposal of plant components, providing a holistic understanding of environmental impacts (ISO, 2006).

Still, the LCA-based study of GHG emissions in HBP is rare in the Nepalese context, although several such studies have been carried out in other parts of the globe revealing varying findings. For instance, Ioannou-Ttofa et al., 2021 found that approximately 90% of lifetime emissions are generated during the operational phase, while in contrast, Zhang & Wang, 2014 reported that two-thirds of emissions were concentrated in the construction phase. Other studies, such as those by Roubík et al., 2020 and Vu et al., 2015 examined the impact of specific feedstocks on overall emissions, demonstrating that GHG emissions vary significantly depending on the type of feedstock used. Hou et al., 2017 emphasized the necessity of including avoidable emissions in assessments, suggesting that poorly managed HBPs could be more prone to higher GHG emissions. Besides these, research by Singh & Gundimeda, 2014, Zhao et al., 2019, Khoshnevisan et al., 2018 etc. explored country-specific emissions scenarios (Supplementary Table S1).

These past LCA studies revealed the inconsistency in the findings. For example, the results were influenced by feedstock type, system boundaries, operational status, and reference system for a particular HBP's LCA study. Besides these, regional factors, sociocultural practices, climatic conditions, and soil conditions have also been identified as influential parameters governing GHG emissions in HBP (Ebner et al., 2015a). Therefore, the adoption of an environmental impact study or GHG quantification conducted under a specific regional condition and scenario may mislead if it is adopted under a different context, such as in the case of Nepalese HBP where the aforementioned parameters and contexts may be different in comparison to other past studies. Therefore, there is a clear need for a more precise and context-specific estimation of GHG emissions and decarbonization potential of HBPs in Nepal and our study aims to fill these gaps by analyzing the GHG emissions scenarios associated with HBPs in Nepal, thereby, evaluating their decarbonization potential within the cooking fuel sector and exploring the opportunities to enhance such potential.

While several LCA studies have demonstrated the environmental benefits of HBPs, none have focused on quantifying their decarbonization potential within the context of a specific country's energy mix. Our study, therefore, introduces a novel application of LCA methodologies to assess HBPs' role in national decarbonization efforts. Moreover, we examined a maximum acceptable ceiling of GHG emissions for HBPs that should be allowed under a particular energy mix, ensuring that HBP emissions remain lower than the avoidable emissions they are intended to substitute. This is crucial to validate their role in decarbonization. Our study also provides a framework identifying which non-cleaner cooking fuels, when substituted by HBPs, most effectively drive decarbonization in the cooking fuel sector. This targeted analysis is essential for developing policies that maximize the impact of HBPs on reducing national emissions, an area with limited existing research. Finally, our approach expands the scope of existing guidelines by incorporating indirect GHG emissions, such as fugitive emissions during operation and the non-utilization of digestate as a fertilizer. These aspects are critical for providing a more comprehensive understanding of the CER potential of HBPs, offering new insights that could significantly shape future policy and practice, and such provisions have been overlooked in the existing guidelines.

The findings of this study can inform policymakers, researchers, and practitioners about the GHG emissions scenario and supporting the development of strategies to mitigate GHG emissions within the HBP sector.

Materials and methods

Theoretical framework

The concept of decarbonization and its quantification in terms of decarbonization potential are the major theoretical framework of our study. Decarbonization means reducing the amount of GHG emissions that a society produces (United Nations, 2015). Key strategies employed in decarbonization of any sector include transitioning to renewable energy sources like biogas, solar, and wind, improving energy efficiency, and electrifying sectors that currently rely on fossil fuels. In addition, emerging technologies such as carbon capture and low-carbon fuels, including biogas and green hydrogen, play a crucial role in this regard. Beyond these technologies, enhancing carbon sequestration through sustainable agriculture and circular economy practices, as well as promoting behavioural changes such as energy conservation and greater use of public transport, are important contributors to reducing emissions and achieving decarbonization (Li & Gou, 2024; Rissman et al., 2020).

Decarbonization potential quantifies the ability of a system, technology, or policy to reduce GHG emissions, thereby contributing to climate change mitigation. Decarbonization potential of a particular sector is measured by tracking the reduction in carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions over time. Several approaches and metrics such as carbon intensity, total GHG emissions mitigation, carbon intensity of GDP, carbon offsets and carbon credits etc. are used to measure decarbonization (Gold Standard Foundation, 2017; International Energy Agency, 2023).

In the context of our study, we estimate the decarbonization potential of HBPs by assessing the extent to which biogas can replace non-clean fuels such as firewood, kerosene, and liquefied petroleum gas (LPG), thereby avoiding the GHG emissions associated with these traditional fuels. Furthermore, we explore ways to enhance the decarbonization potential of HBPs by improving energy efficiency. This includes increasing biogas yield through better operation and maintenance practices, as well as utilizing more digestate as an organic fertilizer within sustainable agricultural systems. Behavioural changes, such as maximizing the use of biogas instead of traditional cooking fuels and utilizing digestate optimally as a fertilizer also contribute to this potential. By quantifying these factors such as fuel substitution, improved energy efficiency, and increased use of organic fertilizer, we can better understand the decarbonization potential of HBPs within the broader framework of Nepal's national efforts to reduce emissions in the cooking fuel sector.

Methodological overview

We employed ISO 14040:2006 and ISO 14044:2006 based LCA framework in this study as methodological framework and concluded our study in six key steps. First, we analyzed the system description and system boundary of HBP system. System description is important to contextualize and understand the key parameters, processes, and operational factors contributing to emissions under Nepalese context. It sets the stage for data collection and analysis for further assessment. Similarly, determination of system boundary delineates the components, processes, and activities of the product/system that are either included in or excluded from the analysis in LCA (ISO, 2006). Second, we conducted a comprehensive field survey to gather emissions inventory and operational data from various HBPs across Nepal.

Based on this data, the surveyed HBPs were classified into two distinct scenarios: Scenario 1 (**S1**), which represents HBPs associated with the minimum possible GHG emissions and serves as the reference scenario; and scenario 2 (**S-2**), which includes all other HBPs that do not meet the criteria for **S-1**. Following this, we estimated the total GHG emissions and assessed the decarbonization potential considering different possible combinations of avoidable emissions. Finally, we explored the impact of varying inventory and operational data of HBPs under **S-2** on the overall decarbonization potential. This step allowed us to identify opportunities for enhancing decarbonization potential within Nepal's HBP sector. Detailed explanation of each step is provided in the subsequent sections.

System description

The system under investigation in this study is the modified Chinese fixed dome type digester, constructed underground using locally available materials promoted by the regulatory body (Fig. 1) (Gautam et al., 2009) and is working with 90% capacity utilization. Various feedstocks including animal dung, kitchen wastes, and human excreta (toilet connection) are potential inputs for the digester which are fed on daily basis. Cow manure was considered as the primary feedstock material due to its prevalence among individual families in rural areas. Cow manure is typically collected in open pits near the HBP site and manually transported to the digester where it is mixed with water in a 1:1 ratio and fed into the digester (based on field survey). The digester retains the mixture for a specified hydraulic retention time as per mentioned in the operating manual provided by the regulatory body (AEPC, 2015). AD of the cow manure produces biogas which is utilized for cooking purposes while the resulting slurry (digestate) produced as a by-product is applied to nearby fields as fertilizer.

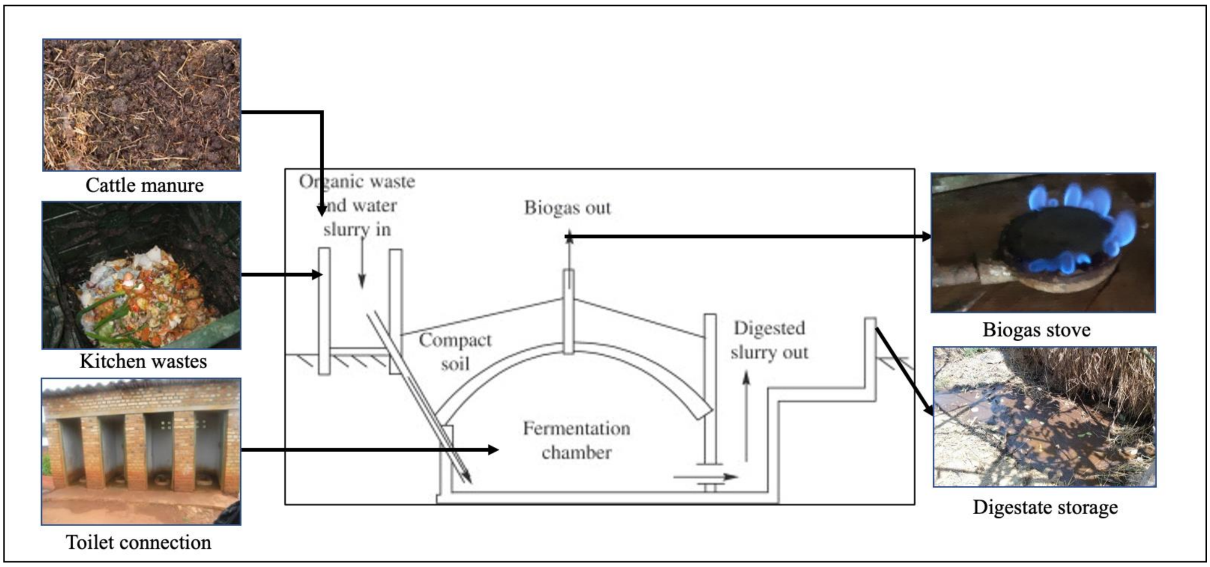
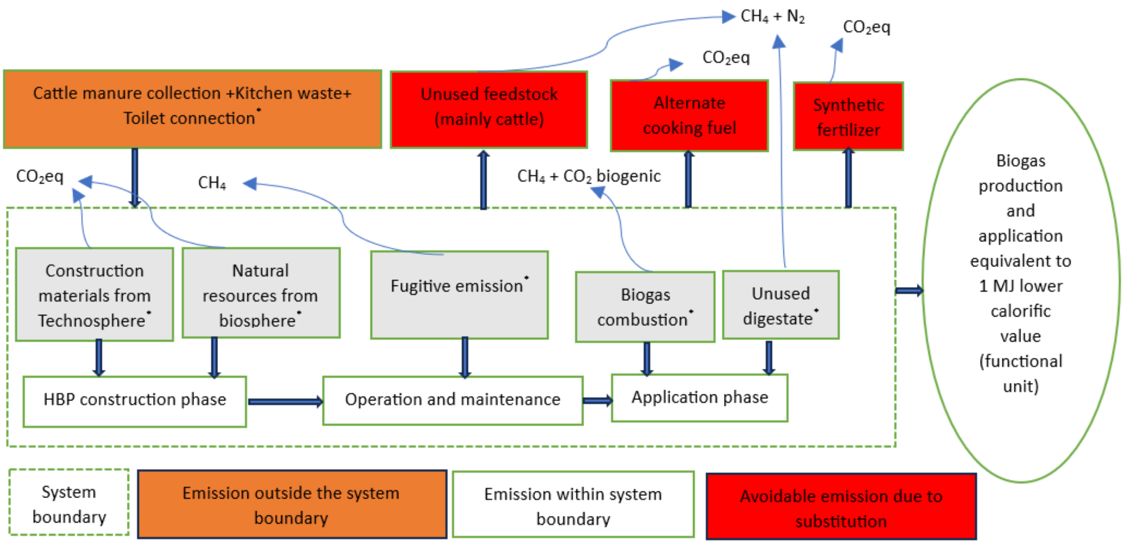


Fig.1. Household biogas plant system in Nepal (Gautam et al., 2009) and interpreted based on author's field visit input

System boundary



* Detailed material and emission inventory as per Table 1

Fig. 2. System boundary of biogas production from a typical household biogas plant in Nepal (Author's interpretation)

The system boundary delineates the components, processes, and activities of the product/system that are either included in or excluded from the analysis in LCA (ISO, 2006). We considered "system expansion" based boundary condition to include avoidable emission from the cow manure in case it could not be used in HBP; substitution of equivalent amount of cooking fuel (traditional & fossil) and synthetic fertilizer with biogas and digestate respectively within the system boundary (Fig. 2). Direct GHG emissions during fugitive and digestate emission and indirect GHG emissions associated with the construction, operation and application phase was included within the system boundary. Digestate emission was too considered within the system boundary however its emission was estimated based on its percentage utilization as fertilizer. GHG emissions associated with the extra construction/ modification except construction of HBP e.g., shade for cattle farming, toilet construction and dismantle of the HBP at the end of the life period were not included in the system boundary as such activities are not carried out exclusively for HBPs under Nepalese context. Similarly, cow manure production was also kept outside the system boundary as the cattle holding by individual household is not exclusively for HBP. Further, the avoidable emissions due to its conversion into biogas was considered during the estimation of decarbonization potential. The system boundary is valid under all scenarios.

Inventory and operational data collection

We conducted a field survey using a semi-structured questionnaire and direct interactions with HBP users to gather comprehensive emissions inventory data of HBP. A total of n = 284 HBPs were selected based on a stratified random sampling method, considering various strata. These strata included: (i) major geographic regions (Hilly, Mountain, and Terai), (ii) functional and non-functional HBPs, (iii) proximity to urban or rural areas, (iv) installation year, and (v) the socioeconomic status of HBP users. Data collection involved multiple methods to ensure a holistic operational assessment. We interacted with HBP users to understand their experiences, challenges like dung storage, leakage emissions and use patterns of biogas and digestate. Additionally, visual inspections of the HBP sites were conducted to assess the physical condition of the plants and their components, including the digester, pipeline valves, outlet, and kitchen stoves. This allowed us to verify the operational status of the HBPs and identify any technical issues, such as construction flaws, maintenance needs, or system failures influencing

GHG emissions. We conducted field survey in January and June of 2022 to cover the impact of climate on biogas yield and associated emissions.

Scenario definition

Based on the field data, such as HBP's technical status (condition of pipeline, valves, digester's structural condition etc.), operational parameters such as feedstock preparation and feeding pattern, fugitive emissions, frequency and quantity of digestate utilization, life period of HBP, we developed two scenarios **S-1** and **S-2**. HBP users' response and visual inspection of HBP sites were considered as the major basis to categorize the HBPs into two different scenarios and such response and observations have been illustrated in Supplementary Table S2, Fig. S1, Fig. S2. We have summarized the comparative analysis of **S-1** and **S-2** in Table 1 for better clarity.

Table 1 Scenario definition

Operational parameter	Value/ range under different scenario		Description/criteria	References
	S-1	**S-2**		
Fugitive emissions	1% of the biogas yield	1%<60% of the biogas yield	- Minimum (1%) fugitive emissions as per suggested by the past similar studies in other countries (S1). - Fugitive emissions ranges from minimum 1% to maximum 60% which has been found possible in developing countries as per suggested by past studies (S2).	(Lansche & Müller, 2017), (Bruun et al., 2014)
Digestate emissions	10% non-utilization of digestate as fertilizer	10%< 100% unutilized digestate i.e. digestate is fully environmental burden		Field survey

Life period	30 years	2 years < 30 years		Field survey
Daily feeding rate	32kg	8kg < 32kg		Field survey
Biogas yield and avoidable emissions	---	Uncertain due to regional, climatic and feed material such as codigestion of dung, kitchen waste, human excreta etc.		Field survey,

In all above-mentioned scenarios, emissions associated with construction phase was considered the same as HBPs are constructed with similar design and made up of same construction materials (AEPC, 2023). Similarly, GHG emissions associated with application phase was considered similar as the produced biogas is used exclusively for cooking purpose under similar cooking stove. Mainly, we considered the GHG emissions associated with operation phase for categorization into two different scenarios. Moreover, avoidable emissions were considered in each scenario to estimate the decarbonization potential. The time frame of our study is applicable throughout the life period of HBP which has been considered twenty years as per suggested by the regulatory body (AEPC, 2015). During field surveys, a range of sizes for HBPs was observed varying from 3 to 12 m^3. For the purpose of this study, the average size of the surveyed HBP (4 m^3) was chosen as the representative size.

Estimation of total GHG emissions under S-1

The phase wise inventory data associated with each stage of the life cycle of HBP in Nepal were collected during field survey. In case primary data was not available from field survey, we referred relevant secondary data. Secondary inventory data were collected through the manual, periodic reports, reference materials and guidelines published by the regulatory body. On some occasions, we cited emission inventory data from relevant scientific literatures however considerations were made to select the data applicable under the Nepalese HBP conditions. Methods used to estimate GHG emissions associated with different phase of life cycle of HBP as well avoidable emissions have been outlined in the next sections.

Construction phase

The details of raw material inventory required for a 4m^3 HBP were listed based on the actual data of construction materials approved by Nepal Biogas Promotion Association (Nepal Biogas Promotion Association (NBPA), 2015), the developer of surveyed HBPs (Table 1). GHG emissions associated with construction materials like burnt solid mud brick, ordinary Portland cement, iron rebar and HBPE pipe were adapted from the relevant secondary scientific studies (Maheshwari & Jain, 2017) (K. M. Rahman et al., 2017; S. M. M. Rahman et al., 2016; Thakuri et al., 2021) During adaption of existing secondary data, it was confirmed that the manufacturing process and transportation condition of such construction materials are almost similar to our context. For example, cement production and its application in Nepal and Bangladesh is almost similar except the energy mix being used during production and hence it was adapted after updating energy mix of Nepal (S. M. M. Rahman et al., 2016). Sand and gravel are naturally available in the river and hence only its transportation related GHG emissions were considered. Sand is transported upto the HBP construction site by diesel operated truck or tractor and such emissions were adapted from Khatiwada et al. (Khatiwada & Silveira, 2009). Naturally available water is employed in hilly districts of Nepal for mixing of sand, gravel and cement whereas manually operated hand pump is used to cater water for the same in Terai districts. Therefore, the emissions related to water use was not included. The material inventory required during the construction phase and associated emissions have been summarized in Table 2.

Table 2 Construction phase inventory analysis of a typical 4 m^3 Household Biogas Plant

Construction materials	Quantity	Unit	GHGs emission/unit ($kgCO_2$ eq)	Total GHGs emission (tCO_2 eq)/per operational year	Reference
*Burnt solid mud bricks	1200	Pcs	0.428	0.0257	(Maheshwari & Jain, 2017)

Ordinary Portland cement	850	kg	0.829	0.035	(Thakuri et al., 2021)
**Sand plus other construction material transportation	50	km	16.16	0.04	(Khatiwada & Silveira, 2009)
***Iron rebar	18	kg	2.248	0.002	(K. M. Rahman et al., 2017)
Iron made components (screws, nails, etc.)	2	kg	2.248	0.022	(K. M. Rahman et al., 2017)
****HDPE pipes	20	m	31.72	0.031	(Hajibabaei et al., 2018)
Local transportation for brick, cement, sand	50	km	0.00075	0.002	(Yang et al., 2018)
GHGs emission during construction phase (tCO2eq/ operational year)	**0.14**				

* Burnt solid mud bricks type having size 22 × 10 × 7 cm

** Diesel operated truck is used for transportation of material in the vicinity of HBPs.
*** Dia 8mm

Operation phase

Fugitive emission from the cracked digester and damaged pipelines/ valves and the emission from unutilized digestate and maintenance activities were the only sources of GHG emissions identified during field survey in operation phase. GHG emissions due to maintenance activities were neglected as the maintenance activities were reported rare during field survey and occasional maintenance activities generates the negligible emissions. Further, all surveyed HBPs are running under ambient condition without any heating arrangements. AD process itself does not consume any external energy and hence no embodied emission was attributed to the AD process. Cow dung and other domestic wastes were considered freely available and near to the plant, so no emission was considered associated with the feedstock production and transportation upto digesters.

GHG emissions due to fugitive emission was estimated based on the following equation:

$$E_f = Pbiogas * Biogas\ leakage\ emission\ in\ \%\ of\ Pbiogas * (Methane\ fraction\ in\ biogas * 25 + N\ fraction * 298) \qquad (1)$$

Where E_{op} is the fugitive emissions in tCO_2eq per operational year, P_{biogas} is the amount of biogas produced per operational year. Only, methane and nitrogen in the biogas are responsible for GHG emissions as other constituent of biogas are negligible. The composition of the constituent gases of biogas was adapted from Singh et al., 2014a; Singh and Gundimeda, 2014)(Supplementary Table S3) and fugitive emissions was estimated accordingly. Detailed estimation of fugitive emission has been described under "Supplementary 2.4".

Quantity of digestate ($DM_{digestate}$) was estimated based on the principle of conservation of mass i.e. the balance mass after deducting the mass of feedstock (FS) converted to biogas.

$$DM_{digestate} = FS - Mass\ of\ biogas\ generated \qquad (2)$$

The detailed calculation to estimate the amount of digestate per operational year has been described under "Supplementary 2.4".

Digestate emissions was calculated based on the IPCC guideline (IPCC, 2006). Methane (CH_4) and nitrogen emission (direct and indirect) are the only responsible for GHG emission from digestate (Roubík et al., 2016) and hence we calculated methane and nitrogen emissions as follows:

- Methane emissions during digestate storage was calculated using modified Tier 2 method as per the equation suggested by IPCC guidelines, 2006 (IPCC, 2006)

$$E_{CH4} = \left[VSdigestate\ *\ B_0 *\ 0.67\ *\ \sum \frac{MCF}{100}\ *\ MS\right] *\ 25 \qquad (3)$$

Where E_{CH4} is the methane emission in tCO_2eq per operational year, VS is the total volatile solid available in digestate in % of total solid, B_0 is CH_4 yield potential of dry matter in m^3/kg, 0.67 is the density of CH_4 in kg m^{-3}, MCF is methane conversion factor of digestate depending upon the manure management system, MS is condition of storage. Appropriate values of these parameters were selected based on the Nepalese climatic conditions from IPCC guidelines and have been included in Supplementary Table S4 (IPCC, 2006). Detailed estimation has been described under “Supplementary 2.4”

Direct nitrogen emission in the form of N_2O and indirect nitrogen emission to air in the form of ammonia and nitrate (converted into N_2O through leaching, volatization and N deposition) were considered in our study (Ebner et al., 2015b). Direct and indirect nitrogen emissions were calculated as per equation (2) and equation (3) as described below (IPCC, 2006):

$$N_{2direct} = \left[DM_{digestate} \, * \, f_{MN} * \frac{EF_3 X44}{28}\right] * \, 298 \qquad (4)$$

Here $N_{2\mathrm{direct}}$ is direct nitrogen emission in tCO_2eq, $DM_{\mathrm{digestate}}$ is the amount of digestate in kg, f_{MN} = N content in digestate, EF_3 = Direct N emission factor. Suitable value of f_{MN} and EF_3 were selected from IPCC guideline and have been indicated in Supplementary Table S4.

Similarly indirect nitrogen emission was calculated using the equation below:

$$N_{2indirect} = \left[DM_{digestate} \, * \, f_{MN} * \left(\frac{Frac_{GasMs}}{100}\right) * \frac{EF_4 X44}{28}\right] * \, 298 \qquad (5)$$

Where $N_{2indirect}$ is the indirect nitrogen emission in tCO_2eq, f_{MN} is N content in the $DM_{digestate}$. Suitable values of f_{MN}, $Frac_{GasMs}$ and EF_4 were selected from the IPCC guidelines and have been included in Supplementary Table S4. Summary of operation phase’s emissions have been illustrated in Table 3 and detailed calculations have been described in Supplementary under suitable headings.

Table 3 Operation phase emissions

Emission category	Quantity	Unit	GHGs emission/unit item ($kgCO_2$ eq)	Total GHGs emission (tCO_2 eq)/annum
Fugitive methane emission	82.12	kg	25	0.1026

Methane emission from digestate	170.97	kg	25	0.213
N_2O emission digestate (direct)	3.564	kg	298	0.053
N_2O emission digestate (indirect)	2	kg	298	0.029
GHGs emission during operation phase (tCO2eq/ operational year)	**0.399**			

Application phase

Biogas generated from HBP is used as the cooking fuel which is combusted in biogas cooking stove and is converted into CO_2 and H_2O. Such CO_2 is considered carbon neutral as it is a biogenic origin (Roubík et al., 2016). Estimation of other constituents of GHG (methane and nitrous oxides) emissions after combustion were adapted from Singh et al and Sadavarte et al. (Sadavarte et al., 2019; Singh et al., 2014b) as they have considered Nepal specific emission factors considering the combustion efficiency of cooking stove under the Nepalese context. Emissions associated with the application phase have been summarised in Table 4.

Table 4 Application phase's emissions

Digester volume 4 m^3	**Quantity**	**Unit**	**GHG emission/unit item ($kgCO_2$ eq)**	**Total GHG emission (tCO_2 eq)/annum**
Emission during combustion at traditional cooking stove				
CH_4 emission	0.00014	kg	25	**0.0398**

Total GHG emissions (A)

Systematic phase-wise emission was calculated in MS Excel sheet. Total GHG emissions associated with HBP during its life cycle phase (**A**) was quantified by adding the emissions associated with its construction phase, operation phase and application phase.

Estimation of decarbonization potential

Life cycle impact assessment and interpretation is the final stage of LCA as per advised by ISO and we interpreted the GHG emissions result in terms of decarbonization potential of HBP. First of all, three primary categories of potential avoidable emissions were identified: emissions mitigation due to the conversion of cow dung into biogas (**a**), emissions associated with traditional and fossil-based cooking fuel (**b**), and synthetic fertilizer (**c**). **a** was estimated similar to the emissions estimated for digestate emissions (Eq 3) as per suggested by IPCC guidelines (IPCC, 2006). However, value of **VS** and consequently methane emissions under this condition were higher in comparison to the digestate (Supplementary 2.4.2). **b** was adapted from Cashman et al. (Cashman, S. Life-Cycle Assessment of Cookstove Fuels in India and China. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-15/325, 2016, n.d.) as the system boundary consideration in the study is similar to our study. As the fossil fuel-based cooking fuels are imported from India, only GHG emission associated with the transport of such fuels have been included as an extra associated emission with these fuels. GHG emissions during the production of N, P and K content of synthetic fertilizer was taken as a basis to estimate avoidable emissions **c** and it was adapted from (Khatiwada & Silveira, 2011). Percentage contribution of cooking fuel mix, estimation of potential avoidable emissions due to the substitution of such cooking fuel and synthetic fertilizers from HBP have been described under "Supplementary 2.5".

After estimating avoidable emissions, we estimated net GHG emissions after subtracting **A** from each category of avoidable emissions (**a**, **b**, **c**) and interpreted it as the decarbonization potential of HBP in tCO_2eq per operational year (Eq. 6, Eq. 7, and Eq.8). The unit of decarbonization potential was adopted as tCO_2eq per operational year to make the unit consistency as the same is the functional unit considered during the GHG emissions estimation. We interpreted decarbonization potential in tCO_2 eq as a unit of global warming potential in 100 years' time horizon (IPCC, 2006).

$$\textit{Decarbonization potential due to avoidable emissions } (\boldsymbol{a}) = \boldsymbol{a} - \boldsymbol{A} \qquad (6)$$

$$\textit{Decarbonization potential due to avoidable emissions } (\boldsymbol{b}) = \boldsymbol{b} - \boldsymbol{A} \qquad (7)$$

$$\textit{Decarbonization potential due to avoidable emissions } (\boldsymbol{c}) = \boldsymbol{c} - \boldsymbol{A} \qquad (8)$$

We further interpreted the decarbonization potential of HBP at the country level in the cooking fuel sector of Nepal considering the cooking fuel mix scenario of Nepal using the same equations (6), (7) and (8). We considered the existing cooking fuel mix portfolio and the cooking fuel consumption data from the official report published by Water and Energy Commissions Secretariat, Nepal (Water and Energy Commission Secretariat Singha durbar, 2022) to estimate **b** on annual basis. Then we estimated the total GHG emissions associated with the number of HBPs required to produce the biogas equivalent to substitute the particular category of cooking fuel. For example, annual consumption of forest wood in the cooking fuel sector in Nepal is around 316 PJ annually and 32254933 number of $4m^3$ sized HBPs are required to produce the biogas equivalent to this energy and substitute the forest wood. Therefore, **b** = Total avoidable emissions associated with 316 PJ and **A** = Total GHG emissions associated with 32254933 number of $4m^3$ sized HBPs. The detailed calculations of decarbonization potential under both **S-1** and **S-2** scenarios considering each category of avoidable emissions at single HBP level and country level have been described in Supplementary 3.1.

Sensitivity analysis

We identified key parameters such as fugitive emission, digestate emission, feeding rate, life period, etc. (Table 1) influencing decarbonization potential of HBPs under **S-1**. Field survey revealed the variation and uncertainties of these parameters under **S-2** and their impact on the decarbonization potential were analysed through sensitivity analysis. Decarbonization potential estimated under **S-1** was selected as the reference scenario during sensitivity analysis.

For example, decarbonization potential was derived assuming a twenty (20) year life cycle period for the HBP under **S-1**. However, observations during field survey revealed that many HBPs became abandoned or non-functional within even three (3) years after the installation and around 3% of visited HBPs were found still operational after three (3) decades. Based on that, we investigated the impact of life cycle period for the range of 3-30 years on the decarbonization potential through sensitivity analysis.

Sensitivity analysis ensured a comprehensive understanding of the significant sensitive factors contributing GHG emissions throughout the lifecycle of HBPs and we proposed targeted mitigation efforts to enhance their decarbonization potential.

Results

In this section, first we describe the decarbonization potential of HBPs under S-1, where optimal conditions with minimum emissions are considered. Next, we analyse the decarbonization potential of HBPs under extreme emissions conditions, as seen in Scenario 2 (S-2), which represents the opposite end of the spectrum with higher associated emissions. Finally, we present the results of the sensitivity analysis, as outlined in the methodological section, to investigate the influence of key operational parameters on the decarbonization potential of HBPs.

Decarbonization potential under S-1

The results demonstrate that the emissions avoided within each category surpass the total GHG emissions associated with HBPs, resulting the significant decarbonization potential of HBPs. However, this potential varies considerably depending on the category of avoidable emissions being substituted. Among the cooking fuel category, substituting forest wood with biogas from HBP was found to be the most effective for decarbonization, yielding the highest annual decarbonization potential (-4.73 tCO_2eq per operational year). Conversely, substituting agroresidue demonstrated the lowest decarbonization potential (0.74 tCO_2eq per operational year). Considering the country's cooking fuel mix scenario and contribution of each category of fuel, substitution of forest wood may decarbonize the sector maximum annually by 150028 kilo tCO_2eq per year due to the significant dominance of the forest wood (around 82% of annual consumption of cooking fuel). Similarly, the decarbonization potential due to the substitution of other cooking fuel category such as dung cake, agroresidue etc were found low due to their lower contribution in the cooking fuel mix as well lower avoidable emissions associated with the production and application of such fuels.

Furthermore, we evaluated the impact of substitution of synthetic fertilizer and utilization of cow dung in HBPs on decarbonization potential, revealing interesting findings. Substituting synthetic fertilizer with an equivalent amount of digestate alone could potentially decarbonize the cooking fuel sector by 0.26 tCO_2eq per operational year. Even utilization of N-content only may be proved sufficient to decarbonize the cooking fuel sector marginally (0.09 tCO_2eq per operational year). Additionally, the avoidance of emissions resulting from the utilization of cow dung in HBPs could be substantial, particularly during summer in Terai districts due to a higher Methane Conversion Factor (MCF). The utilization of cow dung alone in HBPs has the potential to decarbonize approximately 3.63 tCO_2eq per annum considering the country's summer temperature. However, such potential may reach up to as low as 1.293 tCO_2eq per operational year winter in Terai and hilly districts using the suitable recommended MCF value under these contexts by IPCC guidelines (Supplementary 2.5.1).

Under **S-1**, the status of digesters, pipelines, and fittings of HBPs was found to be maintained at the highest level, as detailed in Supplementary Fig. S1. Besides these, regular utilization of digestate in nearby fields of HBP sites was observed. Approximately 10% of visited HBPs were identified under **S-1**, mainly in urban areas.

The decarbonization potential resulting from the substitution of different categories of cooking fuels such as kerosene, LPG, dung cake etc and synthetic fertilizer at the individual HBP level and the country level are summarized in Supplementary Table S6 and illustrated in Fig. 3.

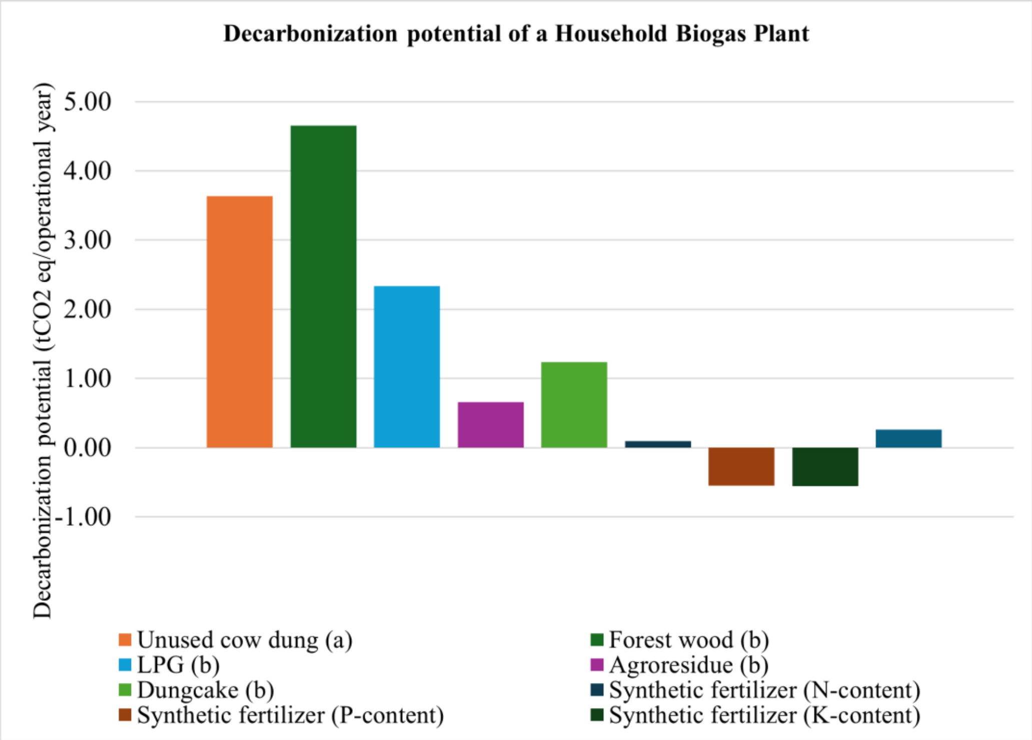


Fig. 3. Decarbonization potential of household biogas plant under **S-1**

Decarbonization potential under maximum emissions condition in S-2

Under **S-2** with the maximum emissions condition, total GHG emissions associated with HBP were estimated to be around 12.73 tCO_2eq per operational year, and the decarbonization potential of HBPs, even considering avoidable emissions at maximum levels (e.g., forest wood), resulted in a net positive emission of at least 7.44 tCO_2eq per operational year hindering their decarbonization feature. Operation phase emissions were found crucial under this scenario, representing the maximum, mainly due to poor conditions of digesters, pipelines, valves, and fittings, as indicated in Supplementary Fig. S2. Furthermore, digestate emissions alone were found to be maximum under this scenario, primarily due to the non-utilization of digestate. The unexpected GHG emissions under this scenario contradict the anticipated decarbonization benefits of HBPs, especially considering that around 23% of surveyed HBPs under S-2 falls in this category.

Sensitivity analysis

The sensitivity analysis investigated the impact of variation and uncertainties in various factors under **S-2** on the decarbonization potential of HBP. The analysis identified feeding rate as the most sensitive parameter influencing the decarbonization potential followed by the digestate emissions, life period, fugitive emissions and biogas yield enhancement (Fig.4). Firstly, the influence of the lifespan of HBPs on their decarbonization potential was explored, revealing a strong correlation between these parameters. Decarbonization potential was quantified to be as high as 7.34 tCO_2eq per operational year, assuming a thirty-year lifespan and considering forest wood as an avoidable category (Supplementary 3.2.1). Furthermore, it was determined that an HBP must operate for a minimum of two (2) years to achieve emissions breakeven i.e. to make equal to the avoidable emissions.

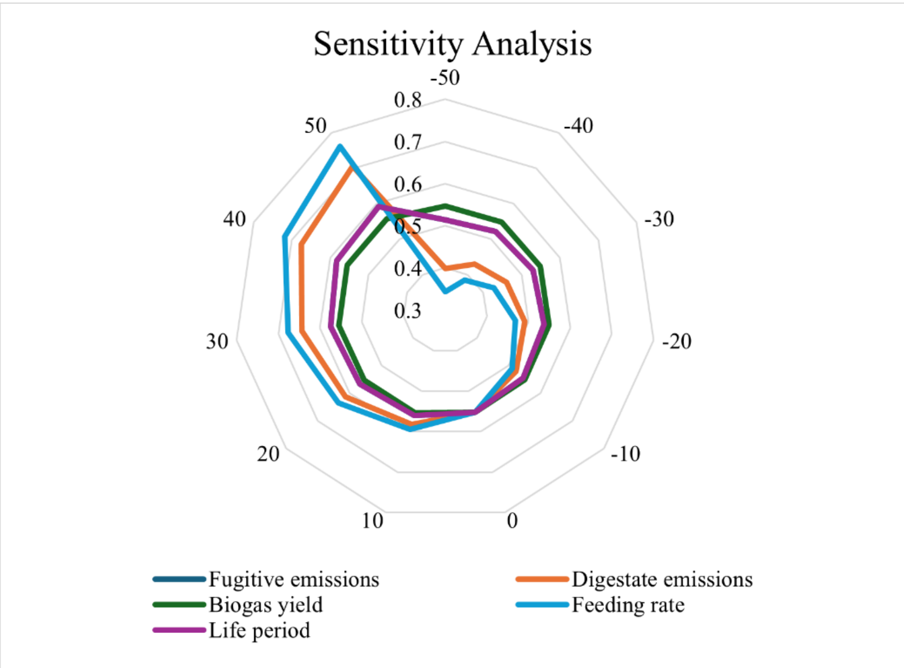


Fig. 4. Sensitivity analysis of major operational parameters

Referring Table 1, fugitive emissions and digestate emissions emerged as the most prominent parameters differentiating the scenarios, impact of these parameters on the decarbonization potential were assessed comprehensively. It was found that the mitigation of fugitive emissions had a significant impact on overall decarbonization potential and even a 4% increment in fugitive emissions resulted in approximately upto 7% lower decarbonization potential (Fig.5). The analysis further revealed that the fugitive emissions should be maintained below 15% to declare HBP as a decarbonizing tool considering each category of avoidable emissions (**b**) as shown in Fig.5. Above 15% of fugitive emissions, HBP cannot decarbonize in case it substitutes cooking fuels other than agroresidue and dung cake. However, substitution of forest wood with the biogas may still validated HBP's marginal decarbonization potential (0.2 tCO2eq per operational year even at 60% fugitive emission).

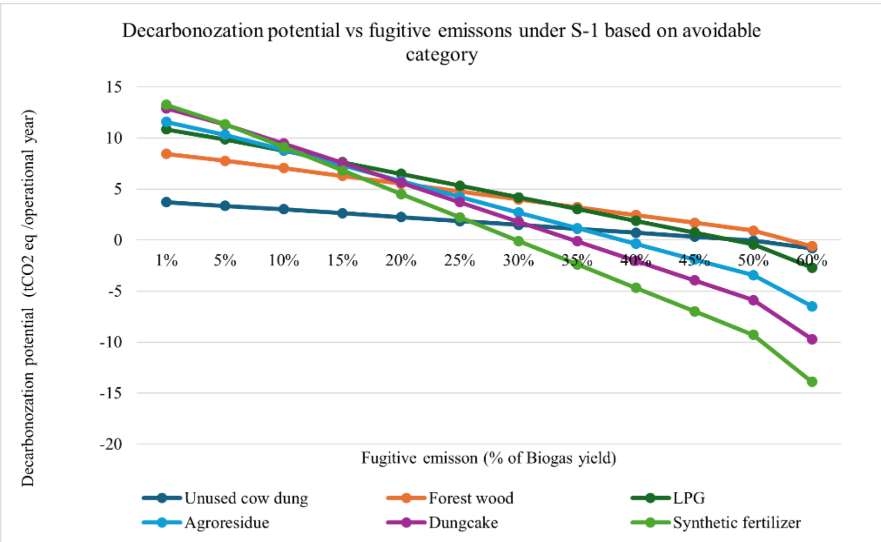


Fig.5. Sensitivity analysis: fugitive emission vs decarbonization potential

The impact of digestate utilization on the decarbonization potential was analysed and the analysis suggested that an increase in the utilization of digestate from 0% to 100% (as in scenario **S-2**) may potentially enhance the decarbonization potential from 1.97 to 5.04 tCO2eq per operational year considering substitution of forest wood which is more than 100%

enhancement of the decarbonization potential. The result further suggests that at least around 15%, 50%, 70% and 80% digestate should be utilized to realize net negative emissions in case LPG, dung cake, agroresidue and synthetic fertilizer is substituted respectively (Fig.6). The relationship between digestate emissions and decarbonization potential should be critically analysed, especially considering that 73% of visited HBPs were found to be operating under scenario **S-2**.

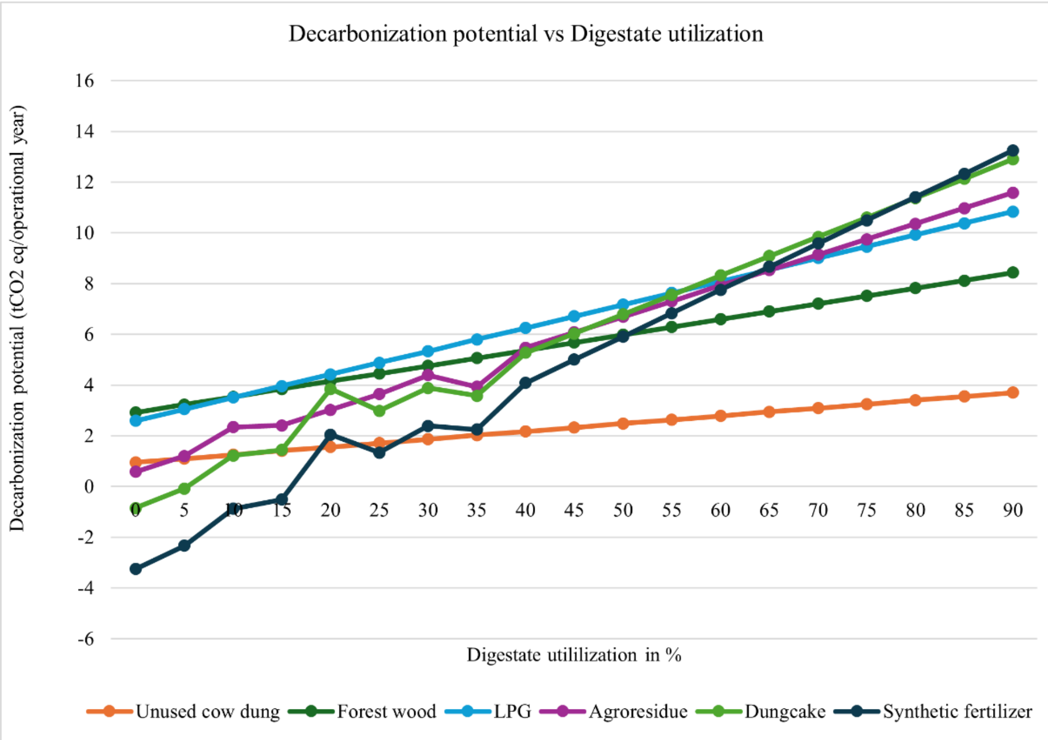


Fig.6. Sensitivity analysis: digestate emission vs decarbonization potential

Furthermore, we observed uncertainty in the feeding pattern too during field surveys although we assumed 32kg feeding on daily basis. To address this uncertainty, we varied the feeding pattern from 8 kg to 32 kg on a daily basis and its impact on the decarbonization potential was assessed. This dung value range was selected for the sensitivity analysis as minimum one cow is essential to feed HBP. Also, dung yield per cow was estimated 8 kg and the maximum number of cows held per household was found four (4) during field survey. The results indicated that daily feeding of around one (1) kilogram of cow dung emits approximately 0.14 tCO_2eq of

GHG per operational year. Interestingly, this emission level can be easily balanced by considering any category of avoidable emissions. The analysis further suggested that lowering down the feeding rate to 8kg (considering the dung yield from one cow) from 32kg (considering the dung yield from four cow) can result around 77% lower decarbonization potential.

We finally assessed the impact of biogas yield on the decarbonization potential. Geographic and climatic conditions were identified different under two broader geographic regions (Hilly and Terai) and during summer and winter season. Such differences resulted uncertainty in the biogas yield and the fugitive emissions too which itself is the function of biogas yield.

Besides it, different GHG emissions from the unutilized cow dung and its impact on the avoidable emissions are expected in Terai and hilly districts during summer and winter. Therefore, appropriate recommended values were adopted from IPCC guidelines (Supplementary Table S4) to accommodate such uncertainties and its impact on the decarbonization potential was assessed. Another important parameter impacting biogas yield is codigestion of feed material. Besides cow dung, contribution of other feed materials such as human excreta, kitchen waste, and goat manure was observed during field survey and their contribution was found uncertain. Considering the uncertainty of biogas yield and its enhancement through co-digestion, we examined its potential impact on the decarbonization potential. Sensitivity analysis suggests even the substitution of synthetic fertilizer under this scenario could potentially result in a decarbonization of 0.38 tCO_2eq per operational year in case biogas yield is enhanced by around 50%. Impact of utilization phase related parameters were neglected during sensitivity analysis as its contribution in total GHG emissions were estimated minimal (around only 6 % of the total GHG emissions).

Discussion

We estimated GHG emissions associated with the production and utilization of biogas at HBP to assess HBP's decarbonisation potential in cooking fuel sector of Nepal. HBP sector in Nepal can be proved as an effective decarbonisation tool and may decarbonize the cooking fuel sector by around 150,000 kilotons CO_2eq annually. However, to maintain and enhance the decarbonisation features of HBP, operation phase and more specifically fugitive emissions and digestate emissions should be mitigated upto the minimum level. Our study revealed some interesting findings pertaining to GHG emissions within HBP system.

First, results of our study confirm that HBPs possess decarbonization potential considering avoidable emissions mitigation due to substitution of cooking fuel and synthetic fertilizer. However, it is crucial to monitor mainly operation of HBP and mitigate GHG emissions to ensure they do not exceed the avoidable emissions levels. This finding aligns with research by Hou et al. (Hou et al., 2017), who suggested that HBPs may not always mitigate GHG emissions from cattle dung under all operating conditions. Further, we revealed that the decarbonisation potential of HBP varies significantly depending upon the regional factor, climatic condition, manure management practice and types of cooking fuel to be substituted by biogas. For example, the decarbonization potential of HBP was found effective in hilly districts as 80% of cooking fuel is supplied from forest wood (WECS, 2022) which associates comparatively the most GHG among the cooking fuels considered in this study (Fig.3). Similarly, significant decarbonization potential of HBP in terai districts was realized due to the avoidance of the emissions from the manure which was utilized in HBPs otherwise significant GHG emissions can be expected from unutilized dung mainly during summer.

Secondly, our findings indicate that the digestate produced by HBPs exhibits sufficient fertilizer quality including nitrogen (N), phosphorus (P), and potassium (K) content

(Supplementary Table S4). This quality justifies HBPs as a decarbonization technology, potentially resulting 30% reduction in GHG emissions through the substitution of synthetic fertilizer alone. Considering the demographic and socioeconomic status of HBP users, and scarcity of synthetic fertilizer during peak season (Gautam S., 2022), the application of digestate as a fertilizer offers additional incentives beyond using biogas as a cooking fuel option besides its decarbonization feature. However, the decarbonization potential of HBPs may be compromised if they are not operated with measures to mitigate fugitive and digestate emissions as suggested by operational data observed during field survey.

Thirdly, sensitivity analysis ensured a comprehensive understanding of the significant sensitive factors contributing GHG emissions throughout the lifecycle of HBPs and targeted mitigation efforts to enhance their decarbonization potential were proposed. We identified GHG emissions mitigation opportunities within each phase of life cycle of HBP to enhance its decarbonisation potential. Our result confirmed that it is essential to operate HBP at least more than two (2) years to justify it as a decarbonization option and the minimum year is slightly higher (3 years) as suggested by Zhang et al. (Zhang & Wang, 2014) Biogas yield and fugitive and digestate emissions considered by them was different than ours. We explored some GHG emissions mitigation opportunities in construction phase of HBP. We found similar emissions associated with HBPs during the construction phase as the common construction material inventory of HBPs are employed during construction. The government regulatory body promoting HBPs has adopted a common design for digesters, such as the GGC fixed dome digester. The GHG emission figures associated with the construction phase align with findings from previous researchers (Ioannou-Ttofa et al., 2021; Zhang & Wang, 2014). However, our study also found significant differences compared to some previous studies, which claimed the construction phase as the major source of emissions, ranging from 79% to even up to 98.46% (Roubík et al., 2016) (Zhang & Wang, 2014). These disparities in results may arise from factors such as the non-consideration of additional constructions like cattle holdings, toilet renovations, and dismantling of HBPs at the end of their lifespan which are different in our case in comparison to the past studies. Field surveys confirmed that such extra constructions are not prevalent in our study area, as they are not exclusively required for HBPs.

We identified the operational phase as the hotspot for GHG emissions due to excessive fugitive and digestate emissions. Visited HBPs are still awaiting maintenance since installation, resulting in poor conditions of digesters, pipelines, valves, etc., with maximum fugitive emissions (60%) considered as per suggested by Lansche et al. (Lansche & Müller, 2017). These findings underscore the complexity of achieving decarbonization goals in the context of HBPs and emphasize the importance of addressing fugitive emissions as a key area for intervention to enhance the overall effectiveness of HBPs in reducing GHG emissions. Reliable quantification of fugitive emissions should be measured to estimate the actual emission scenario for appropriate mitigation actions. However, exact quantification is not a common practice for smaller biogas plants like HBPs in Nepal due to practical difficulties in measurement. Some countries have developed guidelines to predict the percentage of biogas yield as fugitive emissions based on HBP technical status. In the absence of such national guidelines and limitations in actual emission measurement, we considered fugitive emissions under our study as per suggested by Lansche et al. (Lansche & Müller, 2017) and Brunn et al (Bruun et al., 2014) as they had suggested the maximum fugitive emissions in developing countries. Sensitivity analysis confirmed that HBPs can be declared as a technology with decarbonization potential under any scenario through fugitive emissions mitigation alone while keeping other categories of emissions constant. We proposed regular maintenance and replacement of damaged components of HBP as fugitive emission mitigation strategies.

We identified digestate emissions as the second-highest contributor to GHG emissions in HBP due to its underutilization as fertilizer. Farming practices and digestate handling patterns significantly affect the substitution of synthetic fertilizer, which is strongly influenced by socioeconomic practices and geographic locations. It was observed that HBP users apply digestate more frequently in the early phases but become reluctant with relatively older HBPs due to perceived digestate quality degradation. Digestate is often dumped in open pits leading to the loss of N-content and degradation of fertilizer quality, particularly in the summer in Terai districts. Moreover, our study validates previous findings that the simple application of digestate may not fully substitute synthetic fertilizer rather it depends on manure management techniques employed in a particular region or context (Hou et al., 2017). The limited and non-frequent application of digestate to nearby farms adversely affects its utilization and associated emissions. Practical difficulties in transportation and storage of digestate further hinders its full recovery as a fertilizer. Therefore, storage of digestate under shade using locally available resources may mitigate GHG emissions associated with digestate as per suggested by Schoeber et al., 2021. Feedback during field surveys revealed that HBP users are concerned about the poor quality of digestate fertilizer, demotivating its frequent application and resulting in abandonment of HBP. Addressing such concerns may motivate HBP users to continue its use and supportive to the sustainability of around half million existing HBPs of the country. While several digestate management techniques exist for large biogas plants, such as composting, mechanical drying, and physical-chemical treatment, their relevance and feasibility in the HBP sector in Nepal are limited due to users' limited technical knowledge and lack of subsidies for digestate management. Incorporating locally available resources and technologies such as composting digestate with unutilized feedstock, may enhance digestate fertilizer quality.

Biogas yield enhancement influenced the overall decarbonization potential of HBP due to more avoidable emissions substituting more traditional and fossil-based cooking fuel. Co-digestion and daily feeding rate optimization were identified as major influencer through sensitivity analysis to decarbonization potential. This analysis allowed us to explore the implications of incorporating different feed materials and their combinations on GHG emissions and decarbonization potential in HBPs. Our investigation into different combinations of locally available domestic feedstock for biogas production at the laboratory scale revealed promising outcomes. We identified that a combination of food waste, poultry litter, and goat manure in a ratio of 2:1:1 could enhance biogas yield by 24% compared to the mono digestion of cow dung, as considered in our study (Dhungana et al., 2022). Therefore, it is high time to explore more locally available feed material and encourage HBP users to feed optimum especially under the circumstance where daily feeding rate was found inconsistent in the study area.

Besides these, we revealed strong correlation between GHG emissions within HBP system and local context under which HBP is promoted. For example, portable digesters made of rubber, plastic, and other suitable materials should be explored for the locations where regular maintenance is challenging due to unavailability of skilled workers. Portable digesters may be suitable for areas where heavy construction or renovation of residential buildings is expected, as structural cracks were observed in some digesters due to nearby heavy construction during field survey, leading to fugitive emissions. Digesters made of materials like Polyvinyl Chloride, Polyethylene, Neoprene, and rubber are potential options to mitigate emissions compared to concrete digesters like the GGC fixed dome digester. However, comprehensive LCA analyses should be conducted to explore environmental impact categories other than GHG emissions.

Besides these findings, factors such as system boundaries and assumed lifetimes were also identified as contributing parameters responsible for significant variations in results. For example, previous studies suggested a minimum ten-year lifetime of HBPs to achieve net-zero or slightly positive emissions by substituting existing cooking fuels. Our study differs in the consideration of the lifecycle period of HBPs compared to past similar studies and we estimated different emission figure. Although we considered a $4m^3$ digester size for our study, the size of the digester does not significantly influence overall GHG emissions (Ioannou-Ttofa et al., 2021). Therefore, we conclude that the GHG emissions pattern estimated in our study is applicable to digesters installed in any part of the country irrespective of its size.

Our study evaluates the GHG emissions within HBP system in Nepal. However, future studies could delve into the estimation of other environmental impact category associated with HBP like acidification, eutrophication, ozone layer depletion. This would offer valuable insights for comprehensive environmental sustainability analysis.

Conclusion

This study examined GHG emissions from HBPs in Nepal and identified their decarbonization potential in the cooking fuel sector. The study found that HBPs can significantly decarbonize the cooking fuel sector mitigating GHG emissions however effective fugitive and digestate emissions mitigation are essential to ensure and maximize such benefits.

Decarbonization potential of HBPs varies based on factors like fuel substitution, synthetic fertilizer use, and operational practices. To enhance HBP decarbonization, the study proposes strategies such as regular maintenance, proper digestate storage, and using local feedstock to increase biogas yield through codigestion.

Throughout our study, we encountered several challenges. First, logistical issues related to the remote locations of many HBP installations hindered data collection, restricting access to precise operational and emissions data. Second, identifying context-specific factors from IPCC guidelines for emissions estimation proved difficult. Besides these, gathering operational insights from HBP users was challenging due to varying levels of awareness and education regarding HBP technology.

Our study mainly focussed on only one category of environmental impact i.e. global warming potential due to its limited scope. In futures, other aspects of the environmental impact such as acidification, eutrophication, land use etc. can be explored to get insight into overall environmental impact resulting from HBP promotion.

CRediT authorship contribution statement

Navin Kumar Jha: Writing –original draft, Methodology, Investigation, Software, Formal analysis, Conceptualization. Sunil Prasad Lohani: Writing – review & editing, Supervision. Dilip Khatiwada: Writing – review & editing, Methodology. Prajal Pradhan: Writing – review & editing. Shree Raj Shakya: Writing – review & editing.

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Appendix A Supplementary

Supplementary.docx

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