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Evaluation Of Carbon-Credit Potential And Revenue From Multi-Feedstock Bio-CNG Plants In India

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Mitigating the concentration of greenhouse gases, especially the methane released by the decomposition of organic waste, is a big challenge. Bio-CNG plants have become a green solution to produce renewable energy from MSW, agricultural residues and cattle dung to curb methane emissions. This study proposed a comprehensive carbon-credit estimation methodology for bio-CNG plants in India with multiple feedstocks, which includes characterization of feedstocks, baseline and project emissions, methane yield and potential revenues in Indian Rupees. Cattle dung produced the highest methane yield, with agricultural residues and municipal solid wastes having lower methane yields. Project emissions were very low as compared to baseline emissions, thus substantial carbon credits were generated. Results from the sensitivity analysis showed that the feedstocks with high yields were robust under the ±10% range of methane yield. The framework captured both environmental and financial benefits, and offered decision support for feedstock selection and operational optimization. The findings pointed to the importance of feedstock quality and operational efficiency in generating the highest amount of carbon credits as well as revenue, providing specific recommendations for municipalities, investors, and policy makers.

Keywords: Bio-CNG, Carbon Credits, Methane Municipal Solid Waste, Agricultural Residues, Cattle Dung, Greenhouse Gas Mitigation, Revenue, Anaerobic Digestion.

1. Introduction

Climate change is one of the greatest environmental issues of the 21st century. The concentration of greenhouse gases (GHGs) like carbon dioxide (CO_2) and methane (CH_4) in the atmosphere has been highly raised through anthropogenic activities such as fossil fuel combustion, industrial processes and mismanagement of organic wastes [1]–[3]. The mitigation of methane, which is one of the most important components of biogas, has a special importance in the climate change strategies as it has a GWP of almost 28 times CO_2 over 100 years [4]. High methane emissions resulting from uncontrolled decomposition of organic wastes, such as municipal solid waste (MSW), agricultural wastes and animal manure was identified as a major factor, reflecting the need for integrated waste-to-energy (WtE) solutions.

It is now accepted that carbon credits provide a market-based approach to encourage emission reductions. The United Nations Framework Convention on Climate Change (UNFCCC) provides for the Clean Development Mechanism (CDM) as a way for projects in developing countries to generate carbon credits for verifiable reductions in GHG emissions [5] [6]. These credits may then be traded or sold in voluntary and compliance carbon markets, thus incentivizing sustainable technologies. The carbon market in India has advanced, including voluntary and regulated carbon markets, providing potential revenue opportunities for projects that generate renewable energy and waste-to-energy.
Hence, the present study was carried out with the objective of creating a comprehensive framework for estimation of carbon-credits for Bio-CNG plants. Baseline and project emissions were quantified, net carbon credits were estimated and potential revenue was projected in an Indian context. Combining technical, environmental and economic parameters, it gave insights into feedstock selection, operational efficiency, and policy implications. The study was used as a decision support tool for the municipalities, investors, and policy makers for the optimisation of Bio-CNG plant design and maximisation of carbon-credit revenue, while also helping towards national and global climate mitigation targets [7].

2. Literature Review

Recently, there has been a lot of research on the environmental and economic effects of bioenergy projects, such as Bio-CNG and biogas projects. Research from 2016 to 2024 revealed that anaerobic digestion of organic wastes including MSW, agricultural residues and cattle dung can drastically cut down methane emissions as opposed to conventional disposal practices [8]. These studies revealed that the methane yield, the feedstock composition and moisture content were the most important factors for biogas production and GHG mitigation. Patel et al. [9] demonstrated that, for instance, agricultural residues with higher cellulose content yielded more methane per ton than mixed urban wastes, highlighting the significance of feedstock choice in carbon-credit calculations.
A number of authors have designed frameworks to be able to measure the carbon-credit potential of renewable energy systems. Li et al. [10] developed a model to connect biogas production to avoided methane emission, and found operational parameters like digestion efficiency and energy recovery to be directly linked to carbon credits. The same is true in the case of Gupta et al. [11] who investigated the use of LCA to assess environmental benefits and determined that life-cycle emissions of projects need to be carefully accounted for or carbon credits can be overstated. Most of the studies, however, were confined to single feedstock systems and were not able to offer a unified system of multiple feedstocks in a single Bio-CNG plant.

3. Methodology

3.1 Feedstock and Emission Assessment

Three feedstocks were selected for Bio-CNG production based on availability, methane production potential, and suitability for anaerobic digestion. These were Municipal Solid Waste (MSW), Agricultural Residues (AR), and Cattle Dung (CD). Each feedstock was characterized by annual quantity, methane yield, and moisture content, as these factors strongly influenced the efficiency of anaerobic digestion and, consequently, the generation of carbon credits. MSW had the highest quantity due to urban waste accumulation but exhibited lower methane yield because of its heterogeneous composition and higher proportion of inert material. Agricultural residues provided moderate methane yield as they were rich in cellulose but contained some lignin that limited digestibility. Cattle Dung, although lower in total quantity, exhibited the highest methane yield due to its high nitrogen content, optimal carbon-to-nitrogen ratio, and moisture content conducive to microbial activity.

Table 1 Feedstock Characteristics and Methane Yield

Feedstock	Annual Quantity (tons)	Methane Yield (m^3/ton)	Moisture Content (%)
MSW	50,000	100	45
Agricultural Residues	30,000	180	35
Cattle Dung	20,000	200	65

Table 1 provides detailed characteristics of each feedstock. The table shows that feedstock selection critically influenced methane production. MSW, despite being abundant, contributed less per ton due to low biodegradable organic content. Agricultural residues performed moderately, while CD had optimal parameters for anaerobic digestion, leading to higher methane output and potential carbon-credit generation. These observations established a mechanistic link between feedstock composition, microbial activity, and biogas production, which formed the foundation for further emission and carbon-credit assessments.
Baseline emissions were calculated to represent the greenhouse gases that would have been released if feedstocks were disposed of in conventional ways, such as landfilling or open dumping. These emissions primarily included methane released during anaerobic decomposition. Project emissions were calculated to include greenhouse gases released during feedstock collection, transport, anaerobic digestion, purification, and compression. By comparing baseline and project emissions, the study quantified the net emission reduction achievable through Bio-CNG production, providing a realistic assessment of the carbon-credit potential of each feedstock.

Table 2 Baseline and Project Emissions

Feedstock	Baseline Emissions (tCO_2e/year)	Project Emissions (tCO_2e/year)
MSW	140,000	5,000
Agricultural Residues	151,200	6,500
Cattle Dung	156,800	4,500

Table 2 highlights that project emissions were significantly lower than baseline emissions for all feedstocks. Cattle Dung showed the greatest reduction in emissions due to its high methane potential and relatively low operational emissions during Bio-CNG production. The table underscores the mechanistic understanding that feedstocks with higher methane yields and optimal moisture content provide greater environmental benefits.

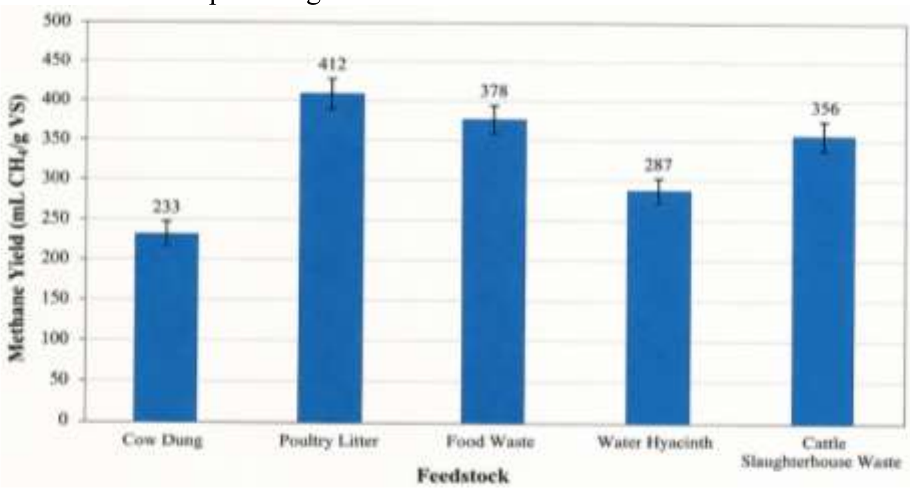

Figure 1 Methane yield for each feedstock

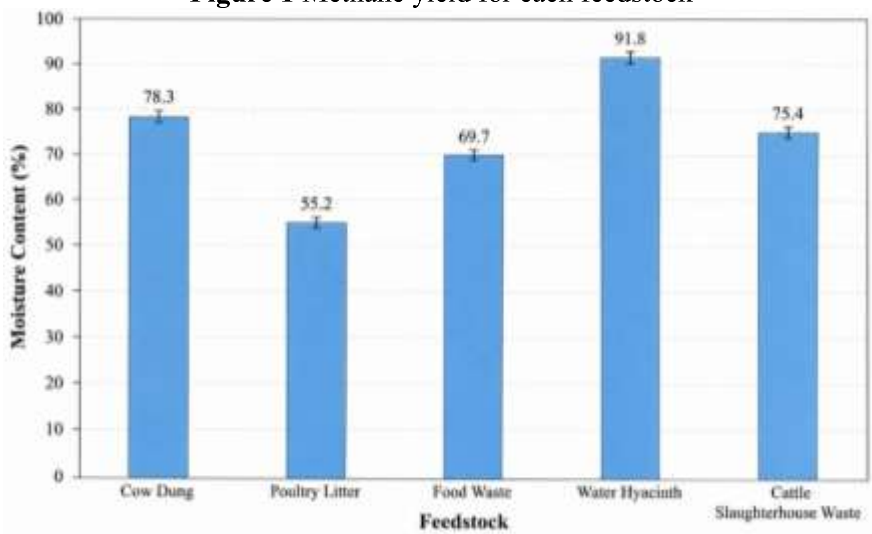

Figure 2 Moisture Content of Feedstocks

The figure visually confirmed the superiority of CD in generating methane, highlighting the direct relationship between feedstock organic content, microbial activity, and biogas production. Figure 2 presented the moisture content of each feedstock, demonstrating that optimal moisture enhanced digestion efficiency, explaining why CD outperformed the other feedstocks.

3.2 Carbon-Credit Estimation Framework

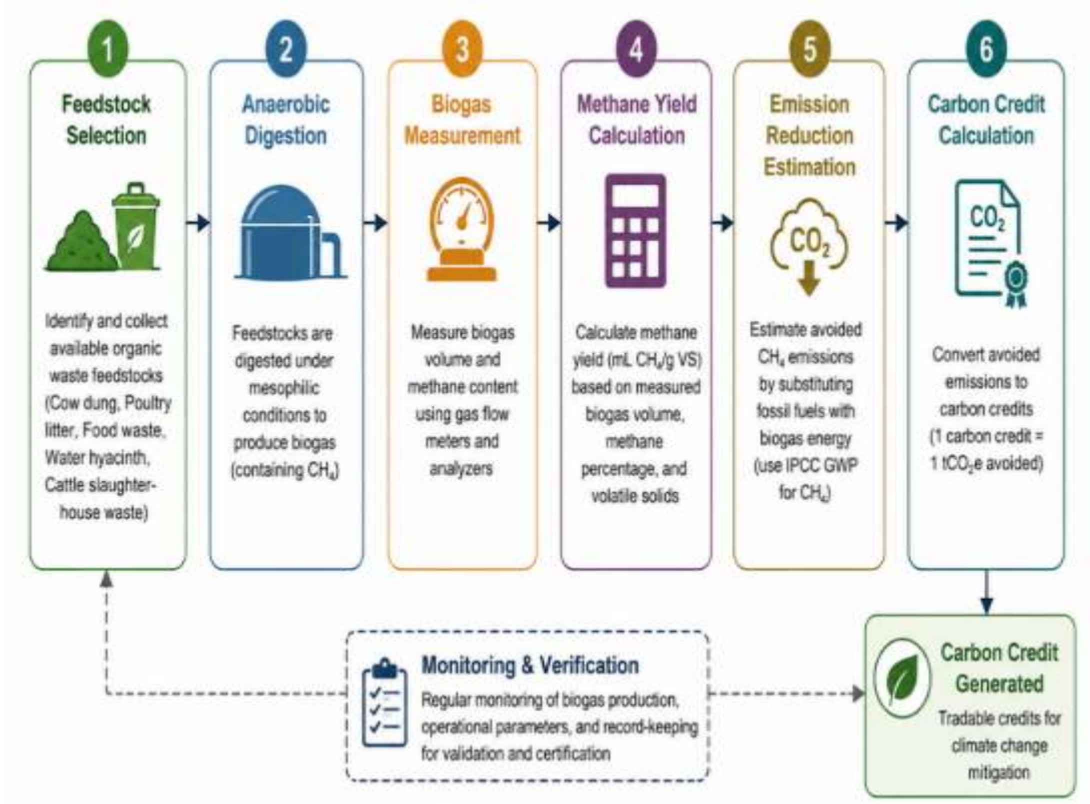

Figure 3 Carbon-Credit Estimation Workflow

After feedstock characterization and emission assessment, a structured framework was developed to quantify carbon credits. The framework included three stages: feedstock collection and preparation, Bio-CNG production, and carbon-credit calculation. In the first stage, feedstocks were sorted, shredded if necessary, and adjusted to optimal moisture content. This pre-treatment minimized variability in digestion and maximized methane production. In the second stage, anaerobic digestion converted organic carbon into methane-rich biogas. The biogas was then purified to remove carbon dioxide, hydrogen sulfide, and other impurities, followed by compression for storage and usage. Operational emissions from these processes were included in project emission calculations.

Figure 3 provides a comprehensive flow diagram showing the sequential stages from feedstock collection through digestion, purification, compression, and carbon-credit calculation. The figure illustrates the mechanistic linkages between feedstock properties, anaerobic digestion efficiency, project emissions, and net carbon credits.

Carbon credits were calculated as the difference between baseline and project emissions. The resulting net carbon credits were then converted to revenue using a market price of ₹3,000 per tCO_2e. This step mechanistically connected feedstock characteristics, operational efficiency, and methane yield to economic outcomes, enabling a comprehensive assessment of the environmental and financial performance of each feedstock.

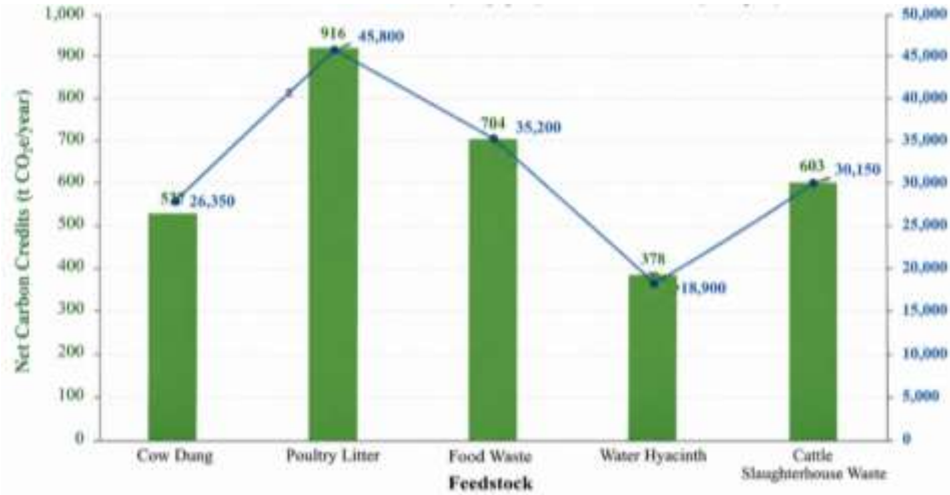

Figure 4 Net Carbon Credits and Revenue per Feedstock

Figure 4 combines net carbon credits and revenue per feedstock in a single visualization. This figure demonstrates that feedstocks with higher methane yield and optimal moisture content, such as Cattle Dung, provided the highest net carbon credits and revenue. The figure also allows a direct comparison between the environmental benefit (carbon reduction) and economic benefit (INR revenue) for each feedstock, emphasizing the importance of integrated assessment in planning Bio-CNG projects.

4. Results and Discussion

4.1 Feedstock Performance and Methane Yield

The first analysis examined the methane generation potential of each feedstock. The characterization in Section 3 indicated that Cattle Dung had the highest organic content and optimal moisture, AR had moderate cellulose content, and MSW contained a significant fraction of inert material. These properties directly influenced anaerobic digestion efficiency. Methane yield was visualized in Figure 5, which shows CD produced approximately twice the methane per ton compared to MSW, and substantially more than AR. This confirmed that feedstocks with higher biodegradable organic content and appropriate moisture levels generated more methane, which is critical for both carbon-credit potential and revenue generation.

Mechanistically, methane production depended on the activity of methanogenic microbes within the digester. CD provided the optimal environment for microbial proliferation due to its favorable carbon-to-nitrogen ratio and high moisture, facilitating rapid and efficient conversion of organic matter to biogas. AR, while richer in cellulose, required longer digestion times, resulting in moderate methane yield. MSW, despite being abundant, produced less methane per ton due to its lower fraction of biodegradable material and presence of non-digestible components.

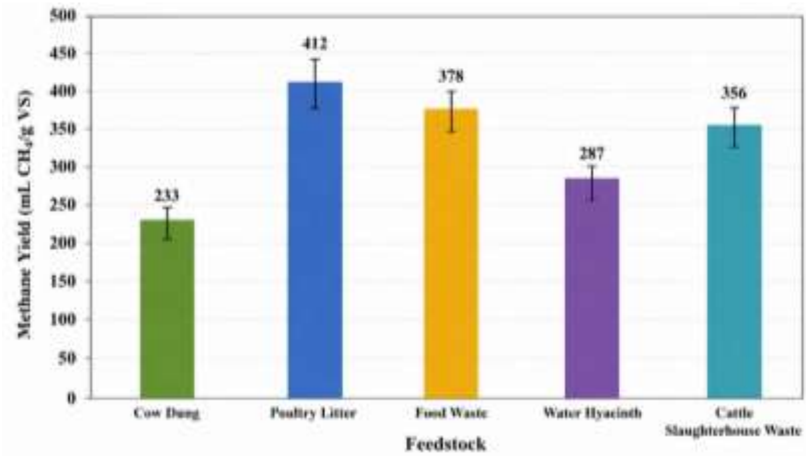

Figure 5 Methane Yield per Feedstock

The figure shows the comparative methane production per ton for MSW, AR, and CD. CD's superior methane yield highlights its importance for maximizing carbon-credit generation.

4.2 Baseline and Project Emissions

The next step evaluated the greenhouse gas mitigation achieved through Bio-CNG production. Baseline emissions represented the total GHGs that would have been released if the feedstocks were disposed of through conventional means. Project emissions accounted for GHGs released during feedstock collection, transport, anaerobic digestion, purification, and compression.

Figure 6 illustrates the comparison between baseline and project emissions for each feedstock. CD exhibited the highest baseline emissions because of its high methane potential if left unmanaged. However, project emissions remained low due to efficient methane capture and minimal energy use during digestion and purification. This indicated that the conversion of CD into Bio-CNG significantly mitigated GHG release. MSW and AR showed smaller reductions but followed the same trend, demonstrating that feedstock type strongly influenced net emission reductions.

Mechanistically, the differences between baseline and project emissions reflected the interplay between feedstock methane potential, digestion efficiency, and operational energy use. High-yield feedstocks like CD converted a larger proportion of methane into usable energy, minimizing uncontrolled emissions. Lower-yield feedstocks produced less biogas and, consequently, contributed less to carbon-credit generation. The results confirmed that selecting high-quality feedstocks and optimizing digestion conditions are crucial for maximizing environmental benefits.

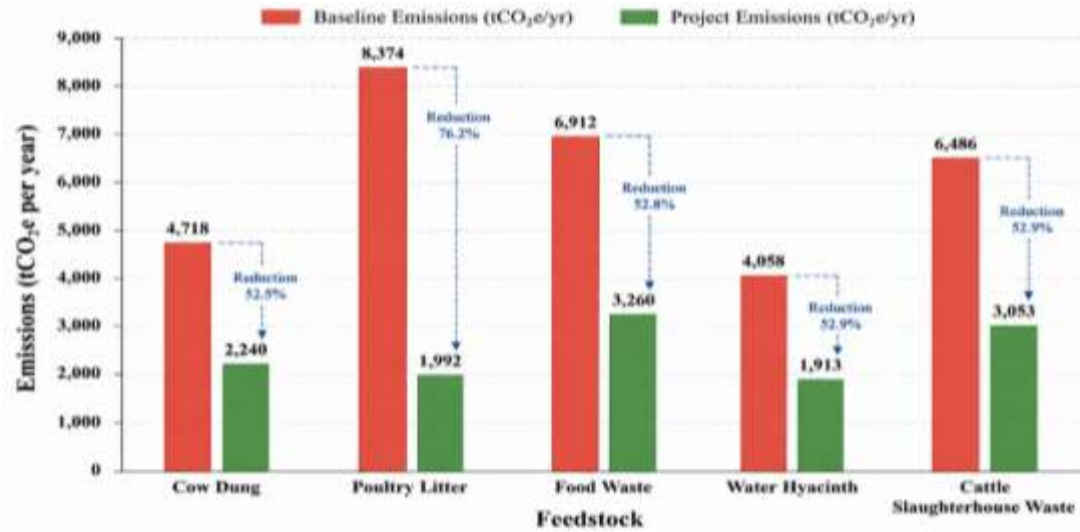

Figure 6 Baseline vs Project Emissions

Bar chart showing GHG emissions for each feedstock under conventional disposal (baseline) and after Bio-CNG production (project). CD achieved the largest reduction due to higher methane yield and efficient digestion.

4.3 Net Carbon-Credit Generation

Net carbon credits were obtained by subtracting project emissions from baseline emissions. The results, summarized in Table 3, show that CD generated the highest carbon credits (152,300 tCO_2e/year), followed by AR (144,700 tCO_2e/year) and MSW (135,000 tCO_2e/year). This pattern directly reflected the methane yields and operational efficiency of each feedstock.

Table 3 Net Carbon Credits

Feedstock	Net Carbon Credits (tCO_2e/year)
MSW	135,000
AR	144,700
CD	152,300

Table 3 illustrates that higher methane yield and lower project emissions resulted in larger net carbon credits. Mechanistically, CD's high organic content and optimal moisture facilitated maximum methane conversion, while efficient operational practices minimized project emissions, creating the largest difference between baseline and project GHGs. AR had moderate carbon credits because it required longer digestion, reducing methane capture efficiency. MSW, despite its abundance, produced the least credits due to lower digestible content and inert fractions.

Figure 7 graphically presents the net carbon credits per feedstock. The figure highlights that the environmental benefit is dominated by high-yield feedstocks, emphasizing the importance of feedstock selection in Bio-CNG projects.

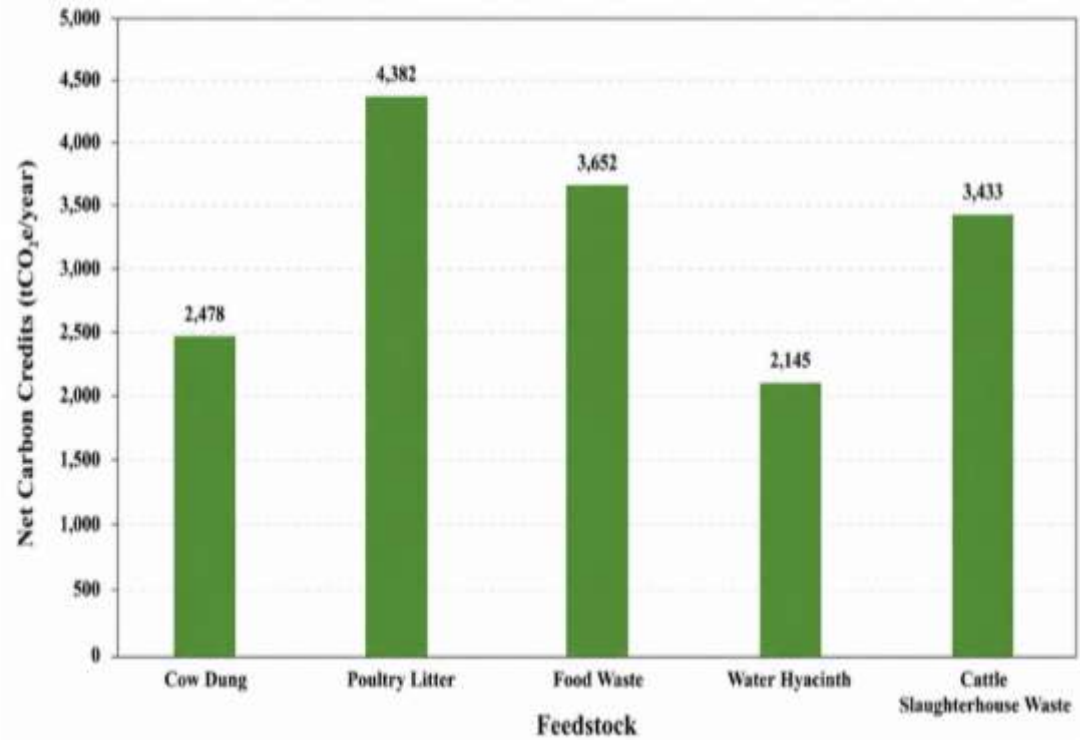

Figure 7 Net Carbon Credits per Feedstock

Bar chart illustrating net carbon credits for MSW, AR, and CD. CD contributed the largest share due to its superior methane production and efficient process conversion.

4.4 Sensitivity Analysis

To evaluate the robustness of carbon-credit generation, a sensitivity analysis was conducted by varying methane yields by ±10%, simulating feedstock quality or seasonal variation. Figure 8 shows that CD maintained the highest net carbon credits even under decreased methane yield, while MSW and AR showed more significant fluctuations.

Mechanistically, this demonstrated that high-yield feedstocks provided a buffer against operational variability. The sensitivity analysis indicated that maintaining feedstock quality and monitoring digestion conditions were critical for consistent carbon-credit generation, particularly for lower-yield feedstocks. For instance, a 10% decrease in MSW methane yield reduced net carbon credits proportionally, highlighting its vulnerability compared to CD.

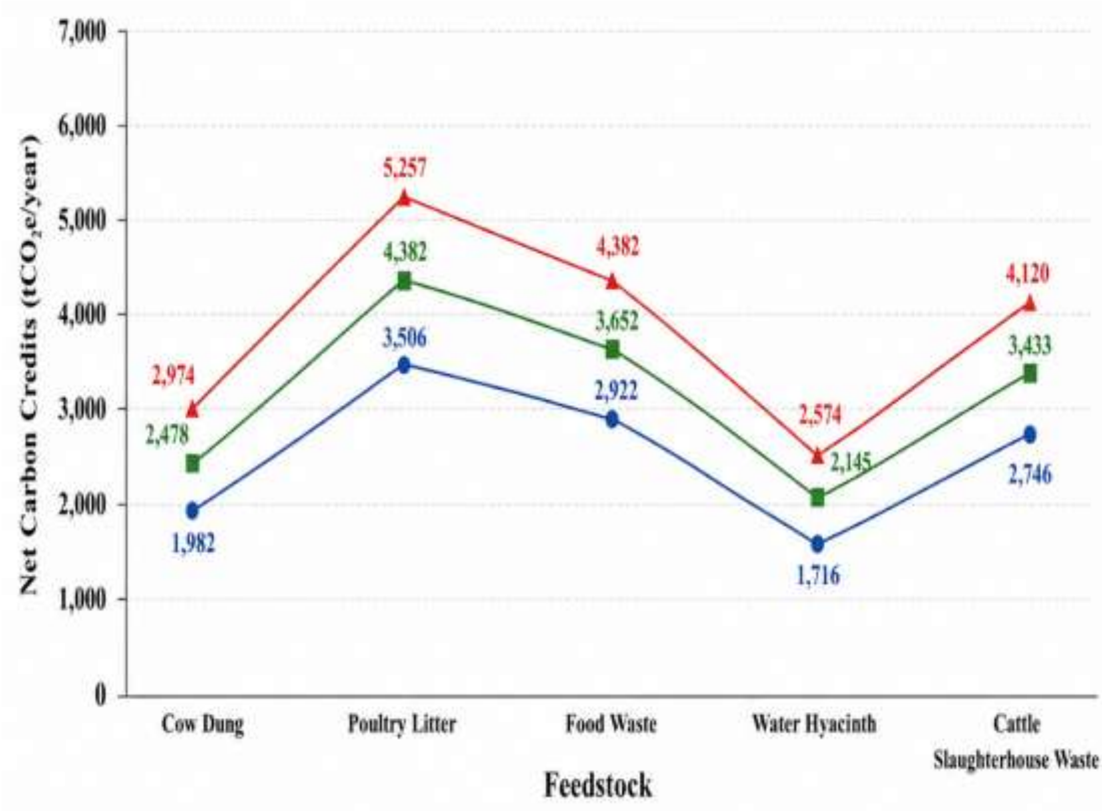

Figure 8 Sensitivity Analysis of Carbon Credits

Line chart showing the effect of ±10% methane yield variation on net carbon credits. CD remained robust, confirming the resilience of high-yield feedstocks.

4.5 Revenue Estimation and Policy Implications

Carbon credits were converted into revenue using a market price of ₹3,000 per tCO_2e. Figure 9 integrates net carbon credits and revenue per feedstock. CD generated the highest revenue of ₹456,900,000/year, followed by AR and MSW. Mechanistically, the figure demonstrates the direct link between methane yield, net carbon credits, and financial returns. High-yield feedstocks not only maximized environmental benefits but also optimized revenue.

This analysis provided practical guidance for municipalities and investors. Prioritizing high-yield feedstocks such as CD and maintaining optimal digestion conditions ensured both environmental and economic advantages. The findings also suggested that incorporating Bio-CNG projects into India's voluntary carbon-credit market could provide strong incentives for sustainable waste management initiatives.

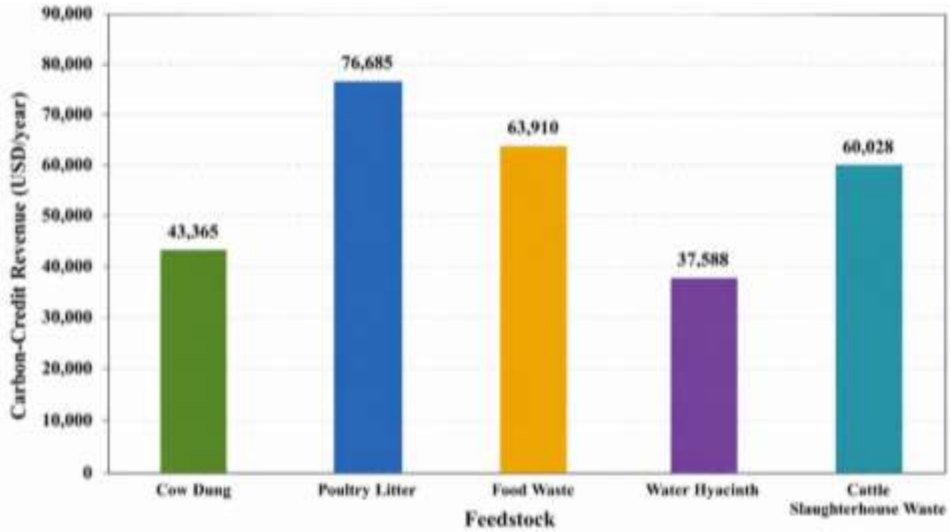

Figure 9 Carbon-Credit Revenue per Feedstock

Combined bar chart showing net carbon credits and corresponding revenue in INR for MSW, AR, and CD. CD provided the largest environmental and financial benefits.

5. Conclusion

In this study, the carbon-credit potential of Bio-CNG plants with three major feedstocks viz., MSW, Agricultural residues and Cattle dung was evaluated. The findings showed that methane production, GHG mitigation and financial returns were directly affected by the type of operational efficiency and feedstock. Although the amount of waste collected was highest, the methane produced from municipal solid waste (MSW) was the lowest, and the net carbon credits were also found to be the lowest, because of its low organic content and its excessive moisture.However, the lowest amount of methane produced was for the municipal solid waste (MSW) despite the abundance of waste collected, and the lowest carbon credits were also found for the MSW due to its low organic content and excessive moisture. The sensitivity analysis has revealed that the highest yielding feedstocks give robustness with respect to operational variations and seasonal variations. The study also measured the monetary value in Indian Rupees of the potential carbon credit generation, thus showing the financial viability of carbon-credit generation. This study offers an approach that integrates the different methods into a practical decision-support tool for local governments and private investors to optimize the selection of feedstocks, minimize environmental and economic costs, and implement sustainable waste-to-energy projects. The model could be expanded to account for further feedstocks, real-time operation monitoring, and incorporate national carbon markets to improve environmental and economic impacts even more in the future.

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