Development of an Intelligent Decision-Support Model for Feedstock Selection and Carbon-Credit Maximization in Multi-Feedstock Bio- Plants

Ravinder Kohli, Dr. Basant Kumar

Abstract: *The selection of suitable feedstocks is essential for achieving stable Bio-CNG production, effective plant-capacity utilization, greenhouse-gas mitigation, and carbon-credit revenue. This study developed an intelligent decision-support model for selecting individual feedstocks and optimizing feedstock blends for multi-feedstock Bio-CNG plants. Municipal solid waste, agricultural residues, cattle dung, food waste, and poultry litter were evaluated using technical, environmental, economic, and operational criteria. The Analytic Hierarchy Process was employed to determine criterion weights, while the Technique for Order Preference by Similarity to Ideal Solution was used to rank the alternatives. Technical, environmental, economic, and operational criteria received respective weights of 0.34, 0.29, 0.23, and 0.14. Among the individual criteria, methane yield, net carbon-credit potential, annual availability, net annual benefit, and project emissions had the greatest influence on feedstock selection. Food waste achieved the highest individual-feedstock closeness coefficient of 0.812, followed by cattle dung, municipal solid waste, poultry litter, and agricultural residues. Five multi-feedstock combinations were subsequently evaluated. The optimized blend containing 35% food waste, 30% cattle dung, 20% municipal solid waste, 10% agricultural residues, and 5% poultry litter achieved the highest decision score of 0.876. It produced an estimated 3.22 million m³ of Bio-CNG annually, generated 35,160 tCO_2e of net carbon credits, attained 95.2% plant-capacity utilization, and provided a net annual benefit of ₹14.18 crore. Sensitivity analysis showed that methane yield and feedstock availability were the most influential parameters, while the optimized blend retained the first rank under all evaluated scenarios. The proposed model provides a transparent and adaptable framework for feedstock procurement, blending, carbon-credit planning, and operational decision-making in commercial Bio-CNG plants.*

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Introduction

The volume of biodegradable waste has been significantly boosted due to fast urbanization, population growth, intensification of agriculture and expansion of food processing and animal husbandry. Organic waste from municipal and agricultural origins, cattle dung, food waste, poultry litter, and agro-industrial by-products are commonly disposed of by open dumping, uncontrolled storage, landfilling or incineration. All such practices result in odour, leachate generation, air pollution, groundwater contamination and GHG emissions. The methane released as a result of uncontrolled anaerobic breakdown of organic waste is especially important due to its high global warming potential. Controlled anaerobic digestion can thus be used to capture this methane, which would help to mitigate environmental pollution, and generate a renewable gaseous fuel [1]-[3].

Anaerobic digestion is a biological process, using microorganisms, to break down biodegradable organic matter in the absence of oxygen. During the process, the gases produced are biogas that is primarily composed of methane and carbon dioxide, with traces of hydrogen sulphide, moisture, ammonia and other trace gases. The purified and separated methane-rich gas can be compressed and utilized as compressed biogas / Bio-CNG. The enhanced gas can be used as an alternative to natural gas and petroleum-based fuels for energy in transportation, industrial heating, cooking, electricity generation, and other uses. The production of bio-CNG can hence be considered as a combined process for both treatment of waste and generation of renewable energy, greenhouse-gas mitigation and resource recovery in one single process [2, 3].

The potential of large-scale production of Bio-CNG in India is quite high as a significant amount of solid waste such as Municipal Solid Waste, Dung of cattle, Agro-Residues, Crop residues, Food Waste and Poultry litter is produced on an annual basis across the country. Nationally promoted plants for waste to energy and compressed-biogas production have helped to establish plants based on local organic resources. In addition to total volume of feedstock, the quality of feedstock, extent of biodegradability, moisture content, volatile solids content, carbon to nitrogen ratio, methane generation capacity, seasonal availability, transportation distance, storage needs, pre-treatment needs are also important factors to the success of a Bio-CNG plant [3]– [6]. Damaged digitizing of feedstocks can lead to unsteady digestion, low methane output, high operating costs, frequent plant shutdown and low use of the installed capacity.

The physical, chemical, and biological properties of the various feedstocks are vastly different. Municipal solid waste is typically available in high quantities in urban environment but because of its mixed nature and contamination with plastics, metals, glass, sand, textiles and other inert materials, the biodegradable part of the waste may be lower than expected. Agri Residues are rich in cellulose and hemicelluloses; however, the microbial degradation is hampered by the presence of lignin, which may need mechanical, chemical, biological or thermal pre-treatment. Cattle dung is rich in moisture, buffering capacity and microbial activity, conducive to stable digestion, but the amount of methane it produces may not be as high as food waste that can be easily digested. Food waste contains a high organic content and can yield high yields of methane; however, the food waste may undergo rapid hydrolysis and acidification that results in accumulation of volatile-fatty-acids and reduction in pH. Poultry litter may have a high organic matter content and a high nutrient level, but can result in ammonia inhibition under high loading rate [7-11].

Several feedstock and operational variables interact with each other and affect anaerobic digestion performance. Methane production and process stability depend on the total solids, volatile solids, moisture content, carbon to nitrogen ratio, pH value, temperature, organic loading rate, hydraulic retention time, particle size, mixing conditions, microbial population and inhibitory substances. A feedstock with high volatile-solids content can have a good methane potential, but it is necessary for microbes to be able to digest the organic matter. Likewise, feedstocks that yield a high laboratory methane production may not be commercially viable if they are not available on a consistent basis, are difficult to transport or require significant pre-treatment [8]-[13].

The present study, hence, proposes an intelligent decision support model for selection of feedstock and maximization of carbon credits in multi-feedstock Bio-CNG plant. The evaluation of MSW, agriculture residues, cattle dung, food waste and poultry litter is done on technical, environmental, economic and operational basis. The criterion weights are calculated using Analytic Hierarchy Process and the rank of the feedstocks is determined by using the Technique for Order Preference by

Similarity to Ideal Solution. The selected multi-feedstock combinations are then evaluated for methane production, Bio-CNG production, plant-capacity utilization, net carbon credits, carbon-credit revenue, operational stability, and overall decision score.

Research Methodology

Annual availability was the amount of material that could be harvested and sent to the plant in a one-year period. Methane yield was expressed in cubic metres of methane per tonne of feedstock. Moisture content, volatile solids, C:N ratio were used as a part of the study because they directly influenced the handling of the substrate, biodegradability, nutrient balance, loading of the reactor and microbial stability. The need for pre-treatment was determined by the degree of sorting, shredding, drying, dilution, thermal treatment, chemical treatment, and/or biological conditioning before the digestion process. Technical performance of each of the feedstocks was assessed by the following parameters: methane yield, volatile solids content, Carbon to Nitrogen ratio, moisture suitability, annual availability, biodegradability, pre-treatment requirement. High CH_4 yield, high biodegradable-organic content, appropriate moisture, balanced nutrient composition and regular nutrient supply were considered as desirable. Intensive pre-treatment, high solids concentration and high risk of inhibition were considered non-beneficial criteria.

Environmental assessment comprised of baseline emissions, project emissions, leakage of methane, avoided landfill or open storage emissions and net carbon credit potential. Baseline emissions included the greenhouse gases that would be emitted if disposal of the feedstock was left unmanaged or as it would decompose naturally. The baseline condition for municipal solid waste and food waste was landfilling/open dumping. Baseline emissions were unmanaged manure storage or decomposition for cattle dung and poultry litter. Agricultural residues baseline: open decomposition, uncontrolled burning, or conventional disposal (as applicable to the adopted reference condition).

The emissions resulting from feedstock collection, transport, sorting, pre-treatment, anaerobic digestion, gas purification, compression, electricity usage, auxiliary fuel consumption, methane leakage, handling of digestate and flaring were all included as project emissions. The project encompassed the entire process of feedstock collection, production of Compressed Bio-CNG and digestate management. All emissions which were not directly related to feedstock diversion or project operation were not included in this defined boundary. The decision criteria were grouped into four major categories: technical, environmental, economic, and operational. Technical criteria included methane yield, volatile-solids content, carbon-to-nitrogen ratio, moisture suitability, annual availability, and pre-treatment requirement. Environmental criteria included baseline emissions, project emissions, methane leakage, and net carbon credits. Economic criteria included feedstock cost, transportation cost, Bio-CNG revenue, carbon-credit revenue, and net annual benefit. Operational criteria included supply consistency, digestion stability, storage requirement, seasonal variation, and plant-capacity utilization.

Results and Discussion

Technical characteristics of 5 selected feedstocks were found to be very different as revealed by comparative assessment. The specific CH4 yield of food waste was high due to the high percent of readily biodegradable carbohydrates, proteins and lipids. Poultry litter also had much methane potential; however, the high nitrogen content meant that there was a high risk of ammonia inhibition. Agricultural residues contained a relatively high fraction of volatile solids, but it gave a lower effective yield of methane due to limitation of microbial attack on cellulose and hemicellulose by the presence of lignin. Cattle dung yielded moderate amount of methane but showed good buffering capacity, moisture content, microbial activity and digestion stability. Municipal solid waste was the most available, but had the lowest usable biodegradable fraction due to contamination and compositional heterogeneity.

Assumed yields of methane from food waste, poultry litter, cattle dung, municipal solid waste and agricultural residues were: 128, 104, 82, 76 and 68 m^3 CH_4/t, respectively. With these values, the choice of the feedstock would have to be based just on the methane yield, which would benefit food waste. Annual availability, transportation distance, pre-treatment, operational stability, baseline emissions and carbon-credit generation, however, were not considered. The specific methane yields of municipal solid waste and cattle dung were thus not competitive enough to compete with other waste sources.

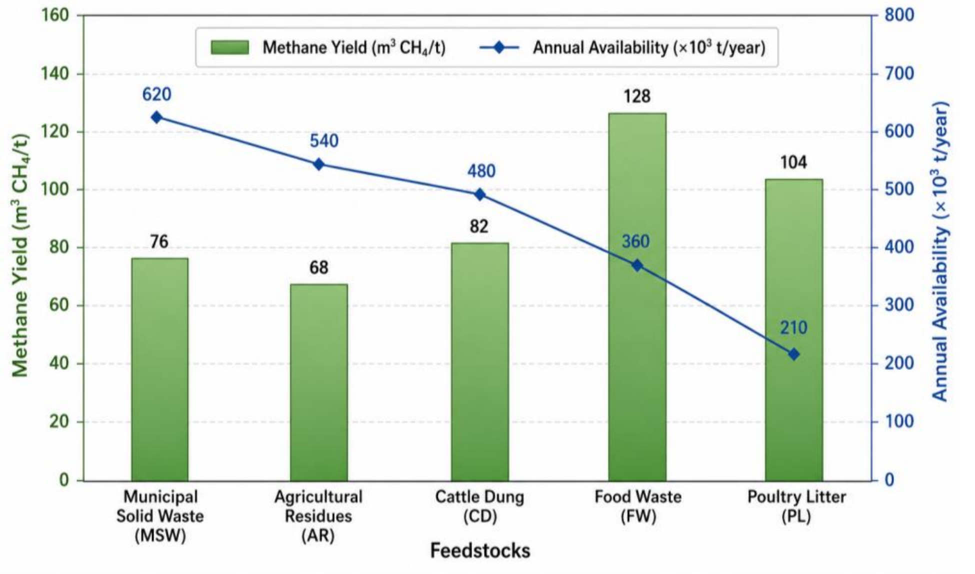

Figure 1. Comparative methane yield and annual availability of selected feedstocks

The methane yield and availability of the selected feedstocks is compared in Figure 1. It can be seen that food waste has the highest amount of methane but it is not as available as that of municipal solid waste and cattle dung in one year. The most valuable solid waste for recovery was municipal solid waste which offered a constant volume of waste for continuous operation of the plant. In addition, there was a large supply of agricultural residues, although seasonal in nature and needing to be stored. Cattle dung was relatively constant throughout the year in areas where there were many cattle. The total recoverable quantity of energy from the poultry litter was low but it was geographically concentrated with high energy potential.

The AHP analysis shown in Figure 1 demonstrated that technical performance was the most influential main criterion, with a weight of 0.34. Environmental performance received a weight of 0.29, followed by economic performance at 0.23 and operational reliability at 0.14. The results indicated that decision-makers placed the greatest importance on methane generation, feedstock quality, emission reduction, and carbon-credit potential. Economic factors remained important but did not outweigh technical and environmental considerations.

Methane yield was assigned the highest individual weight of 0.115, followed by net carbon-credit potential at 0.101, annual feedstock availability at 0.073, net annual benefit at 0.071, project emissions at 0.062, and transportation cost at 0.054. The overall main-criteria comparison matrix produced a consistency ratio of 0.058, and all group-specific consistency ratios remained below 0.10.

Table 1. AHP-derived weights and consistency analysis

Criterion Group	Weight	Consistency Ratio
Technical Performance	0.340	0.061
Environmental Performance	0.290	0.054
Economic Performance	0.230	0.069
Operational Performance	0.140	0.047

Important global sub-criterion weights were: methane yield (0.115), net carbon credits (0.101), annual availability (0.073), net annual benefit (0.071), project emissions (0.062), transportation cost (0.054), volatile solids (0.052), Bio-CNG revenue (0.046), supply consistency (0.043), methane leakage (0.042), and capacity utilization (0.032).

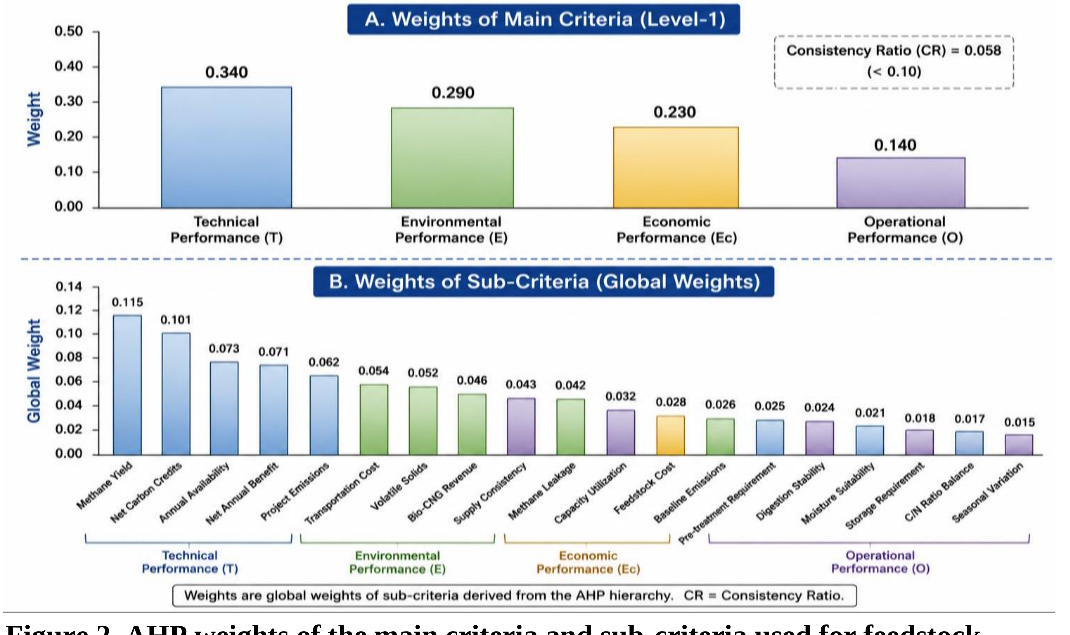

Figure 2. AHP weights of the main criteria and sub-criteria used for feedstock selection

The TOPSIS results shown in Figure 2 ranked food waste as the most suitable individual feedstock, with a closeness coefficient of 0.812. Its superior position was attributed to high methane yield, high biodegradability, limited lignocellulosic resistance, substantial avoided landfill emissions, and strong Bio-CNG and carbon-credit revenue. Cattle dung occupied the second position with a coefficient of 0.694 because it received favourable scores for digestion stability, buffering capacity, supply consistency, low pre-treatment requirement, and compatibility with co-digestion.

Municipal solid waste ranked third with a coefficient of 0.622. It achieved the highest annual availability and considerable baseline-emission avoidance, but heterogeneous composition, segregation requirements, inert contamination, and variable organic fraction lowered its technical and economic scores. Poultry litter ranked fourth with a coefficient of 0.558, while agricultural residues ranked fifth with 0.471 because seasonal supply, low bulk density, high transportation requirements, storage demand, and lignocellulosic pre-treatment reduced their overall score.

The environmental assessment shown in Figure 3 and Figure 4 that food waste produced the highest net carbon credits because it combined high avoided methane emissions with strong methane recovery and Bio-CNG production. Municipal solid waste also achieved substantial baseline-emission avoidance, although sorting, transportation, and pre-treatment increased project emissions. Cattle dung generated lower credits per tonne but performed consistently because unmanaged manure storage represented a credible methane-emission baseline.

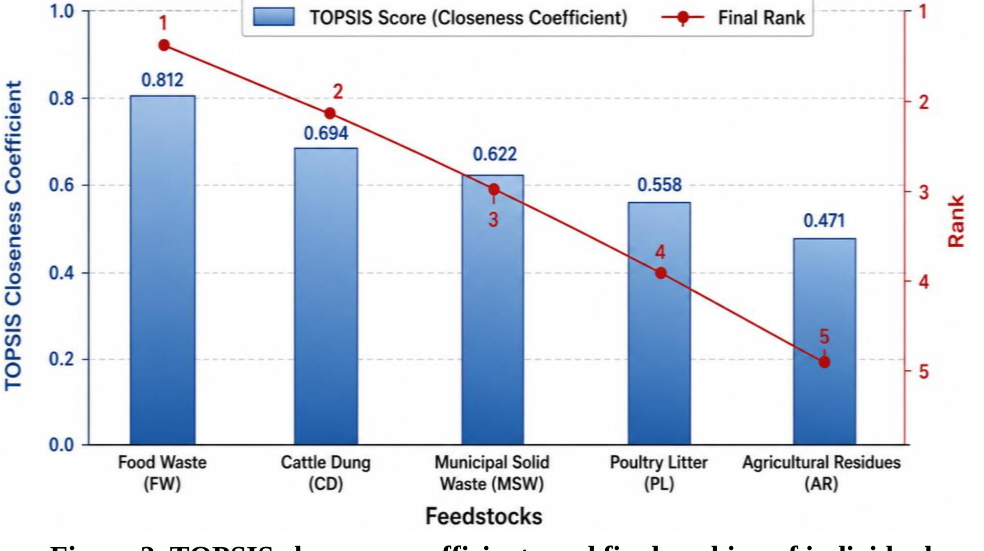

Figure 3. TOPSIS closeness coefficients and final ranking of individual feedstocks

The estimated net carbon-credit generation was 33,860 tCO_2e/year for food waste, 31,740 tCO_2e/year for municipal solid waste, 27,960 tCO_2e/year for cattle dung, 25,480 tCO_2e/year for poultry litter, and 22,610 tCO_2e/year for agricultural residues. At the adopted base carbon-credit price, the corresponding revenues were ₹2.71, ₹2.54, ₹2.24, ₹2.04, and ₹1.81 crore/year, respectively.

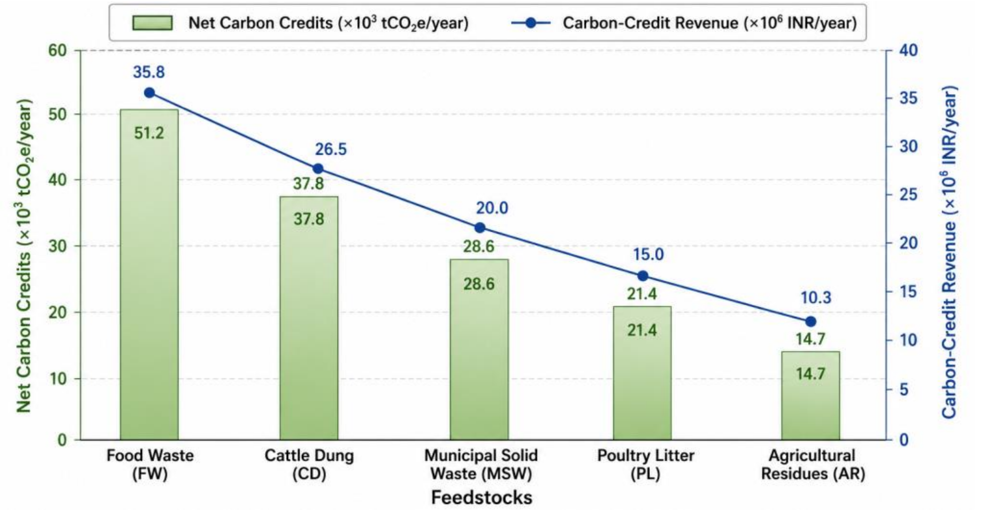

Figure 4. Net carbon credits and carbon-credit revenue of individual feedstocks

Table 2. TOPSIS scores, carbon-credit potential, revenue, and final ranking of individual feedstocks.

Feedstock	Methane Yield (m^3/t)	Net Carbon Credits (tCO_2e/year)	Carbon-credit Revenue (₹ crore/year)	Net Annual Benefit (₹ crore/year)	TOPSIS Score	Rank
Food Waste	128	33,860	2.71	12.84	0.812	1
Cattle Dung	82	27,960	2.24	10.46	0.694	2
Municipal Solid Waste	76	31,740	2.54	10.11	0.622	3
Poultry Litter	104	25,480	2.04	9.32	0.558	4
Agricultural Residues	68	22,610	1.81	8.27	0.471	5

The individual-feedstock analysis demonstrated that no single substrate could simultaneously maximize methane yield, carbon credits, operational stability, and year-round plant utilization. Food waste provided high methane yield but required controlled loading and buffering. Cattle dung provided stability but comparatively moderate energy output. Municipal solid waste provided continuous availability but required effective segregation. Agricultural residues were seasonally abundant, while poultry litter offered high nutrient and methane potential but could not be used safely at an unrestricted proportion. These trade-offs supported the evaluation of multi-feedstock blends.

Five feedstock blends were assessed. Blend 1 contained 50% municipal solid waste, 30% agricultural residues, and 20% cattle dung. Blend 2 contained 40% municipal solid waste, 20% food waste, and 40% cattle dung. Blend 3 contained 30% agricultural residues, 40% cattle dung, and 30% poultry litter. Blend 4 contained 40% food waste, 30% cattle dung, and 30% agricultural residues. The optimized Blend 5 consisted of 35% food waste, 30% cattle dung, 20% municipal solid waste, 10% agricultural residues, and 5% poultry litter.

The optimized blend produced an estimated 3.22 million m^3 of Bio-CNG per year, corresponding to a capacity-utilization factor of 95.2%. Its estimated net carbon-credit generation was 35,160 tCO_2e/year and its net annual benefit was ₹14.18 crore/year. The composite decision score of 0.876 was higher than that of all predetermined blends.

Table 3. Comparative performance and final ranking of multi-feedstock blends

Blend	**Feedstock Composition**	**Bio-CNG Production (million m^3/year)**	**Net Carbon Credits (tCO_2e/year)**	**Capacity Utilization (%)**	**Net Annual Benefit (₹ crore/year)**	**Decision Score**	**Rank**
Blend 1	50% MSW + 30% AR + 20% CD	2.62	28,450	79.3	11.16	0.693	4

Blend 2	40% MSW + 20% FW + 40% CD	2.95	31,980	88.1	12.63	0.781	3
Blend 3	30% AR + 40% CD + 30% PL	2.48	27,110	75.6	10.84	0.654	5
Blend 4	40% FW + 30% CD + 30% AR	3.08	33,420	91.4	13.42	0.824	2
Optimized Blend	35% FW + 30% CD + 20% MSW + 10% AR + 5% PL	3.22	35,160	95.2	14.18	0.876	1

The scenario analysis showed that the optimized blend remained the highest-ranked alternative under most operating and market conditions. A 10% reduction in methane yield reduced annual Bio-CNG production from 3.22 to approximately 2.90 million m^3 and reduced the decision score from 0.876 to 0.821. However, it retained the first rank because its diversified feedstock structure provided better availability and environmental performance than the other blends.

A 20% reduction in food-waste availability had a greater effect on Blend 4 than on the optimized blend. Increasing transportation cost by 20% reduced the attractiveness of agricultural-residue-rich blends. A 20% increase in carbon-credit price improved economic performance without changing the technical or operational ranking. Methane yield was the most influential parameter affecting Bio-CNG production and net annual benefit, while feedstock availability was the second most influential because it directly affected throughput and capacity utilization.

Spearman rank-correlation coefficients ranged from 0.90 to 1.00, confirming that the model provided a generally stable ranking. The integrated decision-support model therefore produced a more realistic selection outcome than methane-yield comparison alone. The superior performance of the optimized blend was associated with complementarity among feedstocks rather than dominance of one substrate.

Conclusions

The AHP results showed that technical performance was the most influential criterion group, with a weight of 0.34, followed by environmental performance at 0.29, economic performance at 0.23, and operational reliability at 0.14. Methane yield received the highest individual weight, while net carbon credits, annual availability, net annual benefit, project emissions, and transportation cost also exerted considerable influence on the final ranking. All pairwise comparison matrices produced consistency ratios below 0.10.

Food waste was identified as the highest-ranked individual feedstock, with a TOPSIS closeness coefficient of 0.812. Cattle dung ranked second because of its buffering capacity, microbial activity, continuous availability, low pre-treatment requirement, and stable digestion performance. Municipal solid waste ranked third because its high annual availability and landfill-emission avoidance were partly offset by contamination, heterogeneity, and segregation requirements. Poultry litter and agricultural residues ranked fourth and fifth, respectively.

The individual-feedstock assessment demonstrated that no single feedstock could simultaneously maximize Bio-CNG production, carbon credits, economic return, digestion stability, and plant-capacity utilization. Among the five investigated combinations, the optimized blend containing 35% food waste, 30% cattle dung, 20% municipal solid waste, 10% agricultural residues, and 5% poultry litter achieved the best overall performance with a decision score of 0.876.

The optimized blend produced an estimated 3.22 million m^3 of Bio-CNG annually and achieved a plant-capacity utilization factor of 95.2%. It generated approximately 35,160 tCO_2e of net carbon credits per year and provided an estimated net annual benefit of ₹14.18 crore. Its diversified feedstock composition reduced dependence on a single waste stream and improved the ability of the plant to maintain continuous operation during seasonal changes in feedstock availability.

The environmental assessment demonstrated that carbon-credit generation was governed by both avoided baseline emissions and project-related emissions. Carbon-credit revenue improved the financial attractiveness of all alternatives but remained supplementary to Bio-CNG sales and digestate revenue. Therefore, a technically unsuitable or operationally unreliable feedstock could not become the preferred alternative solely because of a higher carbon-market value.

The scenario and sensitivity analyses showed that methane yield was the most influential parameter affecting Bio-CNG production and net annual benefit. Feedstock availability was the second most influential parameter because it directly affected plant throughput and capacity utilization. The optimized blend retained the first rank under changes in methane yield, feedstock availability, transportation cost, project emissions, carbon-credit price, and criterion weights.

The developed framework provides a practical decision-support tool for municipalities, Bio-CNG plant developers, investors, plant operators, waste-management agencies, and carbon-credit aggregators. It can support feedstock procurement, supply-contract development, blend formulation, carbon-credit estimation, capacity planning, and adaptation to changes in market and operational conditions.

References

International Energy Agency, Outlook for Biogas and Biomethane: Prospects for Organic Growth. Paris, France: IEA, 2020.

Ministry of New and Renewable Energy, Government of India, “Biogas programme,” New Delhi, India, 2025.

Ministry of Petroleum and Natural Gas, Government of India, “Sustainable Alternative Towards Affordable Transportation-SATAT,” New Delhi, India, 2018.

Ministry of Power, Government of India, “Carbon Credit Trading Scheme, 2023,” Gazette of India, New Delhi, India, Jun. 2023.

United Nations Framework Convention on Climate Change, CDM Methodology Booklet. Bonn, Germany: UNFCCC Secretariat, 2022.

United Nations Framework Convention on Climate Change, “AM0025: Avoided emissions from organic waste through alternative waste treatment processes,” UNFCCC, Bonn, Germany.

A. A. Pilarska, K. Pilarski, A. Witaszek, and K. Boniecki, “Anaerobic digestion of food waste-A short review,” Energies, vol. 16, no. 15, Art. no. 5742, 2023, doi: 10.3390/en16155742.

S. K. Ankathi, S. V. K. Mohan, and R. D. Tyagi, “Sustainability of biogas production from anaerobic digestion of food waste and animal manure,” Methane, vol. 3, no. 1, pp. 29-49, 2024.

W. Lee, J. Park, and H. Kim, “Comparison of anaerobic co-digestion of food waste and livestock manure at different mixing ratios,” Sustainability, vol. 16, no. 17, Art. no. 7653, 2024, doi: 10.3390/su16177653.

R. M. Ahmad, M. A. Khan, and M. S. Hossain, “Optimizing biogas production and digestive stability through anaerobic co-digestion,” Sustainability, vol. 16, no. 7, Art. no. 3045, 2024, doi: 10.3390/su16073045.

S. Qian, Y. Liu, X. Zhang, and J. Wang, “Research on methane-rich biogas production technology and its influencing factors,” Sustainability, vol. 17, no. 4, Art. no. 1425, 2025, doi: 10.3390/su17041425.

C. Bux, E. Amicarelli, and A. L. Lagioia, “Biomethane and compost production by anaerobic digestion of organic waste: Environmental and economic perspectives,” Sustainability, vol. 15, no. 21, Art. no. 15644, 2023, doi: 10.3390/su152115644.

R. Iglesias, R. Muñoz, M. Polanco, and A. Díaz, “Biogas from anaerobic digestion as an energy vector: Current upgrading technologies and future perspectives,” Energies, vol. 14, no. 10, Art. no. 2742, 2021, doi: 10.3390/en14102742.