

Wet/Green Waste to Compressed Biogas: Napier Grass as a Dedicated Feedstock for a Decentralized Waste-To-Wealth Model in Semi-Arid Maharashtra

Akshay Lokhande^{1*}, Dr. Ashok More², Dr. Kundan Kale³

¹Second Year MTech Student, Department of Civil Engineering, D.Y. Patil College of Engineering, Akurdi, Pune

²Professor and Head, Department of Civil Engineering, D.Y. Patil College of Engineering, Akurdi, Pune

³Assistant Professor, Department of Civil Engineering, D.Y. Patil College of Engineering, Akurdi, Pune

*Corresponding Authors Email : lokhandeakshay02@gmail.com

ABSTRACT

Rapid urbanisation in India has sharply increased the generation of biodegradable wet and green waste, much of which is still landfilled, releasing methane and contaminating soil and groundwater. This study evaluates the technical feasibility, energy potential and site suitability of using Napier grass (*Pennisetum purpureum*) as a dedicated feedstock for compressed biogas (CBG) within a Waste-to-Wealth framework for the semi-arid districts of Maharashtra. Napier grass was harvested at three maturity stages (30, 60 and 90 days), characterised for its physicochemical and lignocellulosic composition, and subjected to mechanical size reduction and 2% NaOH alkaline pretreatment. Mesophilic batch anaerobic digestion (35 ± 2 °C) followed VDI 4630 and APHA (2017) protocols, with biogas composition determined by gas chromatography. The 60-day NaOH-treated biomass delivered the highest biochemical methane potential (BMP) of 317 mL CH₄/g VS — a 35.5% improvement over the untreated control. Scaling this to field productivity, one irrigated acre under a six-harvest cycle yields an estimated 8,315 m³ CH₄/year, upgradeable to 9,077 m³ of IS 16087:2018-grade CBG (91.6% CH₄, $\approx$ 82,688 kWh), while avoiding about 26.5 t CO_{2e} and generating a gross profit near ₹3.1 lakh per acre per year. The results establish Napier grass as a high-yield, economically attractive feedstock for decentralised CBG plants aligned with the SATAT and GOBAR-Dhan missions.

Keywords: *Compressed biogas; Napier grass; anaerobic digestion; alkaline pretreatment; biochemical methane potential; circular economy; Waste-to-Wealth.*

I. INTRODUCTION

Rapid urbanisation and industrial growth in India have driven a steep rise in municipal solid waste, of which organic or biodegradable matter wet and green waste accounts for nearly 50–60% of the daily total in most cities. Food residues, vegetable peels, garden trimmings and agricultural residues are still largely deposited in open landfills, where uncontrolled decomposition emits methane, a gas roughly 25–28 times more potent than carbon dioxide, while contaminating groundwater and producing persistent odour. These practices degrade the environment and squander a resource that could be converted into clean energy. Within India's circular-economy agenda, the Waste-to-Wealth concept converts biodegradable waste into bio-fertiliser, compost and, most importantly, compressed biogas (CBG). Produced by anaerobic digestion followed by purification and compression, CBG is a renewable substitute for compressed natural gas (CNG) in transport, power and industrial heating, and supports Sustainable Development Goals 7 and 12. The nutrient-rich digestate that remains can be processed into organic fertiliser, closing the agricultural loop. Figure 1 summarises how organic waste streams, the Waste-to-Wealth concept and sustainability goals interconnect within Indian municipal solid-waste management.

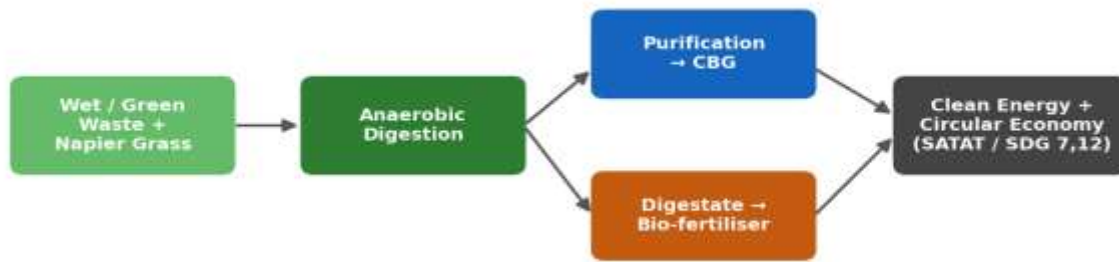


Fig. 1. Conceptual map linking organic waste, the Waste-to-Wealth concept and sustainability goals.

Despite this momentum, existing research concentrates on large municipal waste plants and neglects decentralised, small-scale or hybrid-feedstock models. Napier grass, a fast-growing C4 perennial with exceptional biomass productivity, remains underutilised as a dedicated co-substrate for high-yield biogas, and its biochemical characteristics, pretreatment needs and suitability for semi-arid Maharashtra have not been systematically investigated. This study therefore evaluates the technical feasibility, energy potential and site suitability of Napier-grass-based CBG and integrates it with wet/green-waste conversion into a scalable Waste-to-Wealth model. Its objectives are to characterise the grass across maturity stages, identify the most energy-efficient harvest age, map suitable semi-arid cultivation zones, and assess large-scale deployment.

II. LITERATURE REVIEW

The literature consistently positions anaerobic digestion of biodegradable municipal and agricultural waste as a viable route to high-quality CBG that reduces landfill burden and greenhouse-gas emissions while generating decentralised economic value. Reviews by Saravanan (2025) and Igbokwe et al. (2022) frame biomass valorisation within the circular bioeconomy, while Jameel et al. (2024) and Singh & Chakrabarti (2023) survey biogas fundamentals and the practical barriers — high capital cost, weak feedstock supply chains and approval delays — that constrain CBG adoption in India. Kumar & Banerjee (2021) review thermochemical routes such as pyrolysis and gasification for biochar, bio-oil and syngas. A substantial body of work targets Napier grass specifically. Kubde et al. (2023) compared conventional and advanced pretreatments and confirmed that its lignocellulosic fibres require pretreatment before efficient saccharification. Pomdaeng et al. (2022) reported methane yields up to 367 mL CH₄/g VS from a two-stage continuous reactor, and Kriswantoro et al. (2024) found that 1:1 co-digestion of Napier grass with hydrolysed food waste reached 614 mL CH₄/g VS at 67% methane. Chanpla et al. (2018) demonstrated that harvesting age strongly governs total solids, lignin content and C/N ratio, while Wilawan et al. (2014) optimised C/N ratio and organic loading in co-digestion with chicken manure.

Pretreatment studies by Dahunsi (2019) showed that acid and thermo-alkaline treatments substantially reduce hemicellulose and solubilise cellulose, and silage work by Herrmann et al. (2011) indicated that lignin is inversely correlated with specific methane yield. Across the wider feedstock landscape, Reza et al. (2020) and Rocha et al. (2017) characterised the thermochemical and combustion properties of elephant grass, Antunes et al. (2021) explored biorefinery use of its carbohydrate fractions, and Lewin et al. (2024) benchmarked perennial energy grasses against silage maize. The recurring gap is clear: limited systematic evaluation exists of process efficiency, methane yield and energy recovery for alkaline-pretreated Napier grass under Indian semi-arid conditions, and of its integration with urban wet waste in decentralised systems. The present work addresses that gap, resting theoretically on the four stages of anaerobic digestion — hydrolysis, acidogenesis, acetogenesis and methanogenesis together with lignocellulose-degradation kinetics and GIS-based weighted-overlay site-suitability principles.

III. MATERIALS AND METHODOLOGY

An applied experimental design combined laboratory batch digestion, biomass characterisation, gas analysis and GIS-based site assessment. Napier grass — selected for its high biomass yield, rapid growth and drought tolerance — was the primary feedstock. Samples were collected from agricultural fields in the Pune, Solapur and Ahmednagar districts

of Maharashtra and harvested at three growth stages: 30 days (young), 60 days (mid-mature) and 90 days (mature), to capture the influence of maturity on biogas yield. Biomass was washed, mechanically chopped to a mean particle size of 3 ± 0.5 cm, and subjected to alkaline pretreatment using 2% (w/v) NaOH at a 1:10 solid-to-liquid ratio for 24 hours, followed by washing to neutral pH. Alkaline pretreatment saponifies the ester linkages between hemicellulose and lignin and solubilises lignin by cleaving α -aryl ether bonds, swelling the cellulose structure and increasing microbial accessibility. Untreated samples served as controls. Physicochemical analysis followed APHA 2540B (total solids) and 2540E (volatile solids); lignocellulosic fractions were determined by Van Soest NDF/ADF/ADL procedures and C/N ratio by CHNS elemental analysis.

Batch anaerobic digestion was conducted in 5-litre borosilicate reactors flushed with nitrogen and sealed for strictly anaerobic conditions at 35 ± 0.5 °C in a temperature-controlled bath. The substrate-to-inoculum ratio was 0.5 g VS/g VS per VDI 4630, with total solids near 8%. Daily biogas was measured by acidified-saline liquid displacement and corrected to standard temperature and pressure, while composition (CH_4 , CO_2 , H_2S , NH_3) was analysed every alternate day by gas chromatography with a thermal-conductivity detector. Quality assurance comprised triplicate runs, control and blank digesters, regular calibration, continuous pH/temperature monitoring and cross-validation against literature. The experimental matrix — three maturity cohorts $\times$ two pretreatment conditions plus controls, in triplicate — gave 21 digesters per cycle and 63 units across three cycles, with sample sizes fixed by power analysis ($\alpha = 0.05$, $\beta = 0.20$, effect size = 0.8).

Table 1. Physicochemical composition of Napier grass at three maturity stages.

Parameter	Unit	30-day	60-day	90-day	Method
Moisture content	%	78.2	71.6	65.3	APHA 2540B
Total solids (TS)	% FM	21.8	28.4	34.7	APHA 2540B
Volatile solids (VS)	% TS	87.3	84.6	79.2	APHA 2540E
Cellulose	% DM	32.4	36.8	41.2	Van Soest
Hemicellulose	% DM	18.7	22.3	25.6	Van Soest
Lignin (ADL)	% DM	6.8	9.4	13.2	Van Soest
Carbon (C)	% DM	41.3	43.8	46.2	CHNS
Nitrogen (N)	% DM	2.34	1.87	1.42	Kjeldahl
C/N ratio	—	17.6	23.4	32.5	Calculated

FM = Fresh Matter; DM = Dry Matter; TS = Total Solids. Means of triplicate determinations.

As Table 1 and Fig. 2 show, maturity drives consistent trends: total solids rise from 21.8% to 34.7% as moisture declines, volatile solids fall from 87.3% to 79.2% of TS as recalcitrant material accumulates, and lignin nearly doubles from 6.8% to 13.2%. Critically, the C/N ratio climbs from 17.6 at 30 days to 32.5 at 90 days, crossing the optimal 20–30 digestion window precisely at the 60-day stage (Fig. 2).

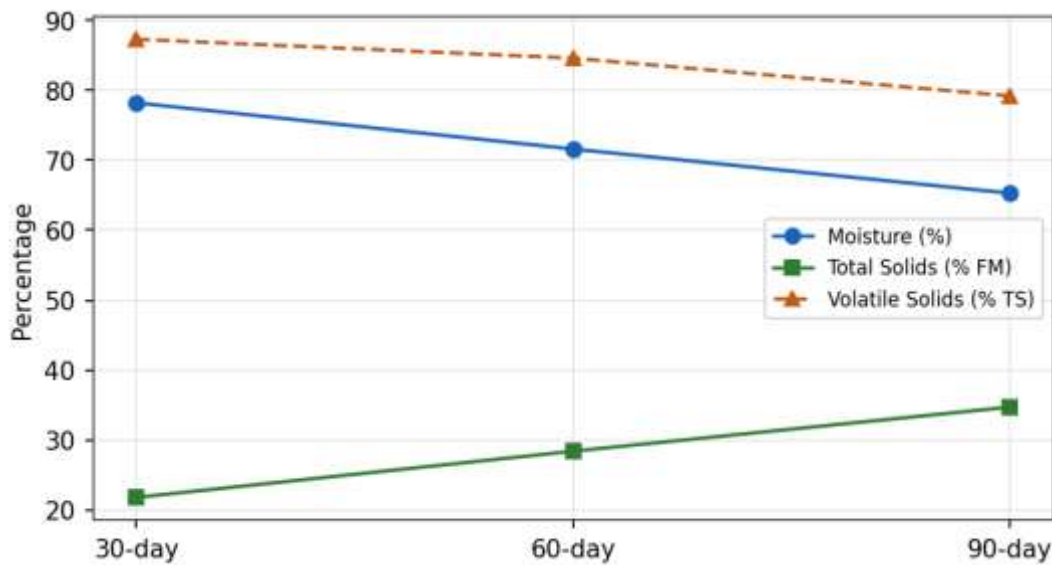


Fig. 2. Moisture, total-solids and volatile-solids trends with maturity.

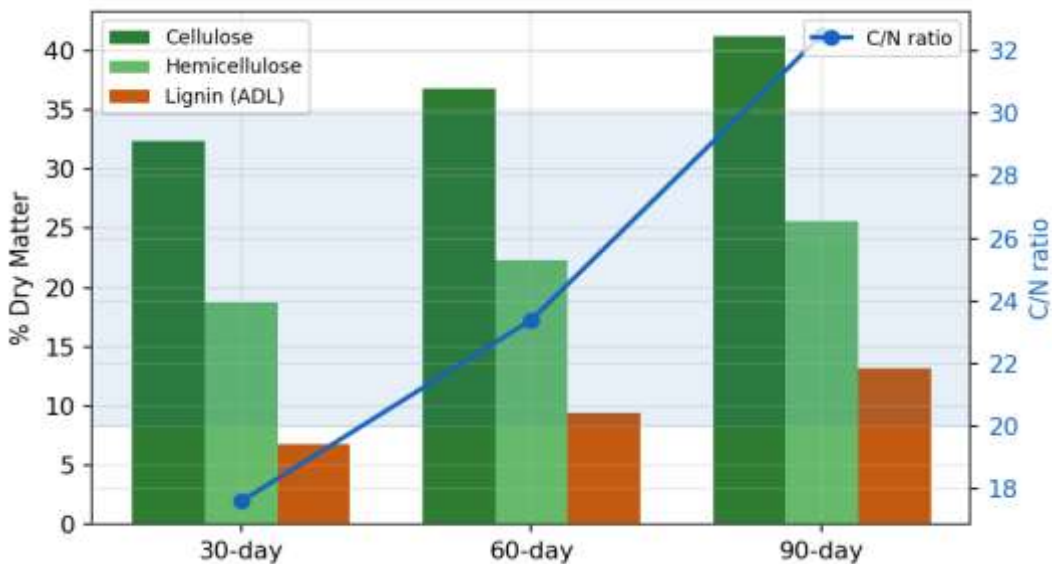


Fig. 3. Lignocellulosic composition and C/N ratio across maturity (optimal C/N band shaded).

IV. RESULTS AND DISCUSSION

A. Methane Potential and Pretreatment Effect

Gas-chromatographic analysis at peak production (day 20) showed that NaOH pretreatment consistently raised methane content and suppressed CO₂ and H₂S, with the 60-day treated biomass peaking at 61.4% CH₄. Table 2 and Fig. 4 quantify the biochemical methane potential. The highest BMP — 317 mL CH₄/g VS — was recorded for the 60-day NaOH-treated sample, a 35.5% gain over its untreated control, consistent with its near-optimal C/N ratio of 23.4. The 30-day stage produced less (267 mL CH₄/g VS) owing to high moisture and low VS loading, while the 90-day stage gave the lowest yield (234 mL CH₄/g VS) because its elevated lignin resisted solubilization at 2% NaOH. Treatment also shortened the lag phase from 4.8 to 3.4 days at 60 days, indicating faster hydrolysis.

Table 2. Biochemical methane potential (BMP) and biogas yield (n = 3).

Maturity	Pretreatment	Biogas (mL/g VS)	CH ₄ (mL/g VS)	Lag (days)
30-day	Untreated	388	203	5.2
30-day	NaOH-treated	462	267	3.8
60-day	Untreated	421	234	4.8
60-day	NaOH-treated	517	317	3.4

90-day	Untreated	356	179	6.8
90-day	NaOH-treated	418	234	5.1

Best: 60-day NaOH-treated biomass at 317 mL CH₄/g VS (35.5% enhancement over control).

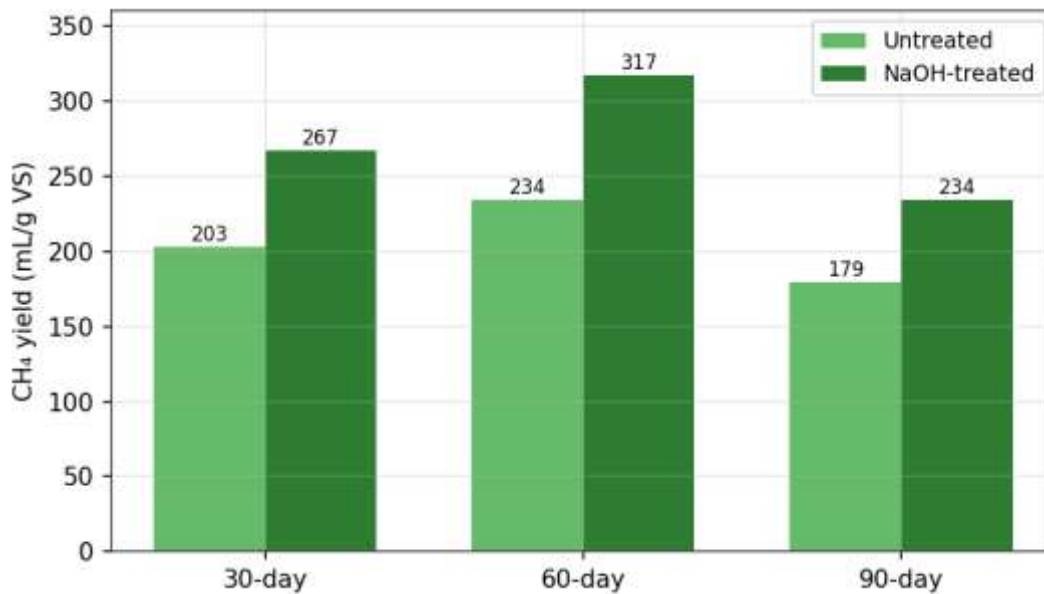


Fig. 4. Methane yield by maturity stage and pretreatment condition.

B. Process Stability and Biogas Upgrading

Over the 35-day retention period, pH stayed buffered between 6.8 and 7.4 and the VFA/alkalinity ratio fell from 0.21 to 0.09, confirming a healthy methanogenic environment in the best reactor. A two-stage purification train — activated-carbon adsorption for H₂S followed by pressurised water scrubbing for CO₂ — upgraded the raw biogas to vehicular grade (Table 3, Fig. 5): methane purity rose from 61.4% to 91.6%, CO₂ fell below 2%, H₂S below 5 ppm, and energy content rose from 21.9 to 32.8 MJ/m³, exceeding the IS 16087:2018 specification.

Table 3. Biogas purification performance versus IS 16087:2018.

Parameter	Raw biogas	After purification	IS 16087:2018
CH ₄ (%)	61.4	91.6	≥ 90
CO ₂ (%)	33.8	< 2.0	≤ 3
H ₂ S (ppm)	385	< 5	≤ 5
Moisture (mg/m ³)	Saturated	< 30	≤ 32
Energy content (MJ/m ³)	21.9	32.8	≥ 32.3

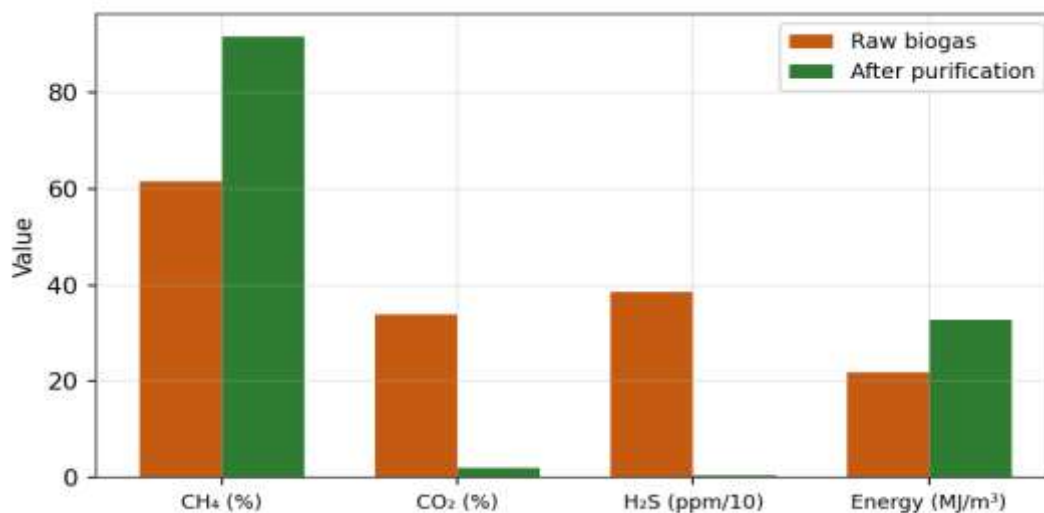


Fig. 5. Raw vs. purified biogas (H₂S shown as ppm ÷ 10 for scale).

C. Field-Scale Biomass and Energy Yield

The experimental BMP was scaled to realistic field productivity using the input parameters in Table 4. Agronomic yields reported per hectare were converted to a per-acre basis (1 ha = 2.471 acres). The irrigated fresh-matter yield of 45 t/ha per 60-day harvest gives 18.21 t FM/acre/harvest, and over six harvests, 109.15 t FM/acre/year. Applying the measured 60-day moisture (71.6%) and VS fraction (84.6% of TS) yields 31.00 t TS and 26.23 t VS per acre per year (Table 5).

Table 4. Key input parameters for the 1-acre calculation.

Parameter	Value	Source / Basis
Harvest frequency	6 cuts/yr	60-day cycle $\times$ 6 $\approx$ 360 d
Fresh biomass yield	45 t FM/ha/harvest	ICAR-IGFRI; irrigated
Moisture content (60-day)	71.6%	Lab measurement (Table 1)
VS fraction	84.6% of TS	Lab measurement (Table 1)
BMP (NaOH, 60-day)	317 mL CH ₄ /g VS	BMP test (Table 2)
CH ₄ in CBG	91.6%	Purification (Table 3)
CH ₄ density (STP)	0.717 kg/m ³	Ideal gas law
CBG selling price	₹55/kg	MoPNG Gazette, Jan 2024
CO ₂ factor (CNG)	2.75 kg CO ₂ e/kg CH ₄	IPCC AR6, 2021

Table 5. Stepwise annual biomass yield (1 acre, 60-day cycle).

Step	Parameter	Formula	Result	Unit
S3	Fresh biomass / harvest	45×0.4047	18.21	t FM/acre
S5	Annual fresh biomass	18.21×6	109.15	t FM/yr
S8	Annual total solids	109.15×0.284	31.00	t TS/yr
S10	Annual volatile solids	31.00×0.846	26.23	t VS/yr
S11	Annual VS (grams)	26.23×10^6	2.623×10^7	g VS/yr

Methane volume follows by applying the BMP to the annual VS mass:

$$V(\text{CH}_4) = 2.623 \times 10^7 \text{ g VS} \times 317 \text{ mL/g VS} \approx 8,315 \text{ m}^3 \text{ CH}_4/\text{year}$$

Since methane forms 61.4% of raw biogas and is upgraded to 91.6%, the raw biogas volume is 13,543 m³ and the CBG volume 9,077 m³/year. The methane mass is 5,962 kg, and at an LHV of 35.8 MJ/m³ the annual energy is 297,677 MJ $\approx$ 82,688 kWh — enough to power roughly eighteen average homes, or to displace about 6,558 kg of CNG, 6,458 kg of LPG and 7,004 kg of diesel annually. The theoretical Buswell yield for 60-day biomass is 390–420 mL CH₄/g VS, so the measured 317 mL CH₄/g VS represents 76–81% of theoretical, typical for lignocellulosic feedstocks.

Table 6. Annual biogas, energy and revenue summary (1 acre).

Parameter	Result	Unit
Annual methane volume	8,315	m ³ CH ₄ /yr
Raw biogas volume	13,543	m ³ /yr
CBG volume (IS 16087)	9,077	m ³ /yr
Methane mass	5,962	kg CH ₄ /yr
Annual energy	297,677 / 82,688	MJ / kWh
CNG / LPG / diesel equivalent	6,558 / 6,458 / 7,004	kg/yr
CO ₂ e avoided (CNG only)	16,396	kg/yr
CBG + digestate revenue	4,60,470	₹/yr

Because Napier grass regrows uniformly, each of the six harvests contributes an equal 18.21 t FM and 4.37 t VS, producing 1,386 m³ CH₄ and 1,514 m³ CBG per cut, with cumulative methane rising steadily to the annual 8,315 m³ (Fig. 6).

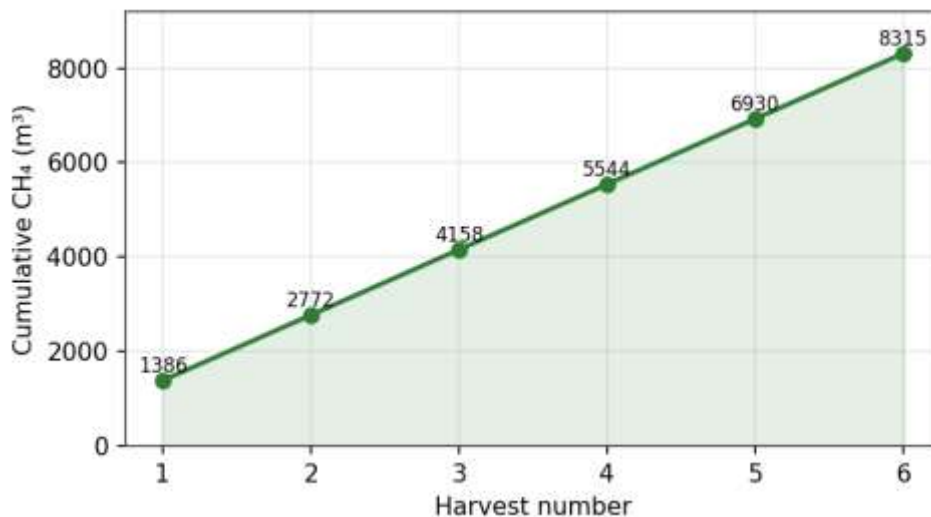


Fig. 6. Cumulative methane production across the six annual harvests.

D. Comparative Productivity

The annual 31.00 t TS/acre is exceptionally high for a dedicated energy crop. As Fig. 7 shows, irrigated Napier grass is roughly five to six times more productive than energy maize and two to three times more productive than Miscanthus per unit area, owing to its C4 photosynthesis, perennial regrowth and six-harvest cycle. Combined with a 10–15-year stand life and tolerance to periodic water stress, this makes it an outstanding feedstock for decentralised CBG plants.

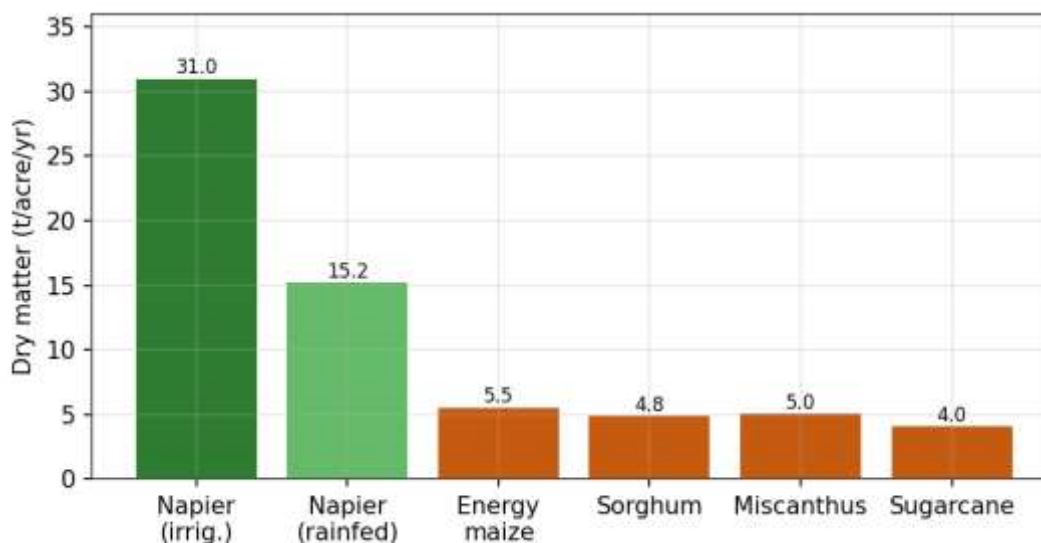


Fig. 7. Comparative annual dry-matter productivity of energy crops (per acre).

E. Digestate, Environmental and Economic Outcomes

Assuming 55% volatile-solids destruction, mass balance gives 16.57 t DM/acre/year of nutrient-rich digestate, recovering 470.6 kg N, 268.4 kg P₂O₅ and 212.1 kg K₂O — equivalent to roughly 1,022 kg urea, 575 kg SSP and 354 kg MOP — and meeting all FCO 2016 bio-fertiliser thresholds. Environmentally, displacing fossil CNG avoids 16,396 kg CO₂e/year directly, and capturing methane that would otherwise escape from field-left residue adds 10,136 kg CO₂e, giving total avoidance of about 26.5 t CO₂e/acre/year (Fig. 8).

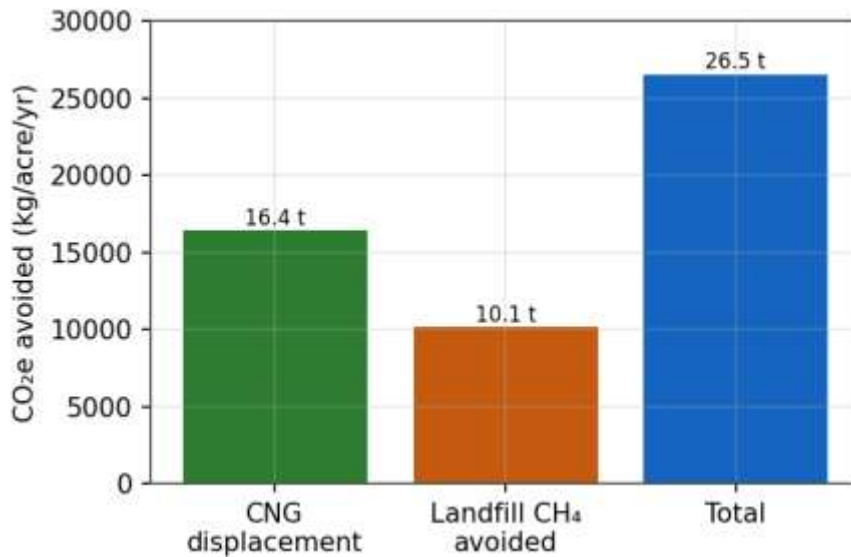


Fig. 8. Annual greenhouse-gas avoidance from CNG displacement and landfill-methane capture.

Economically, the system earns ₹3,27,910 from CBG and ₹1,32,560 from digestate, for ₹4,60,470 gross revenue; after ₹1,50,000 operating cost, the gross profit is ₹3,10,470 per acre per year before capital recovery (Fig. 9). Table 7 consolidates the full annual balance across biomass, energy, environment and economics.

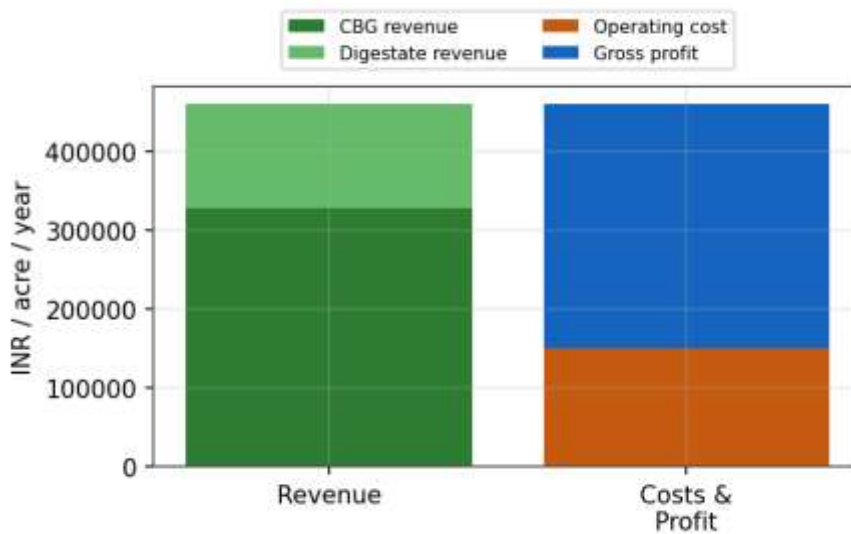


Fig. 9. Annual revenue composition and gross profit per acre.

Table 7. Comprehensive annual output summary — 1 acre of Napier grass.

Category	Parameter	Annual value
Biomass	Fresh biomass yield	109.15 t FM
Biomass	Volatile solids yield	26.23 t VS
Energy	Methane volume	8,315 m ³ CH ₄
Energy	CBG volume (IS 16087)	9,077 m ³
Energy	Energy output	82,688 kWh
Environment	Total GHG avoidance	26,532 kg CO ₂ e
Environment	Digestate produced	16.57 t DM
Environment	Synthetic fertiliser replaced	~1,951 kg NPK
Economics	Total gross revenue	₹4,60,470
Economics	Operating costs	₹1,50,000
Economics	Gross profit	₹3,10,470

F. Sensitivity Analysis

A one-at-a-time sensitivity analysis (Fig. 10) examined how a $\pm 20\%$ variation in each key input shifts the baseline methane output of 8,315 m³/year. Fresh-biomass yield, BMP value and volatile-solids fraction each propagate the full $\pm 20\%$ change directly, ranking them as the highest-leverage parameters, whereas moisture content and harvest frequency exert only moderate influence. This focuses future optimisation on agronomic yield maximisation, pretreatment efficiency and precise VS characterisation.

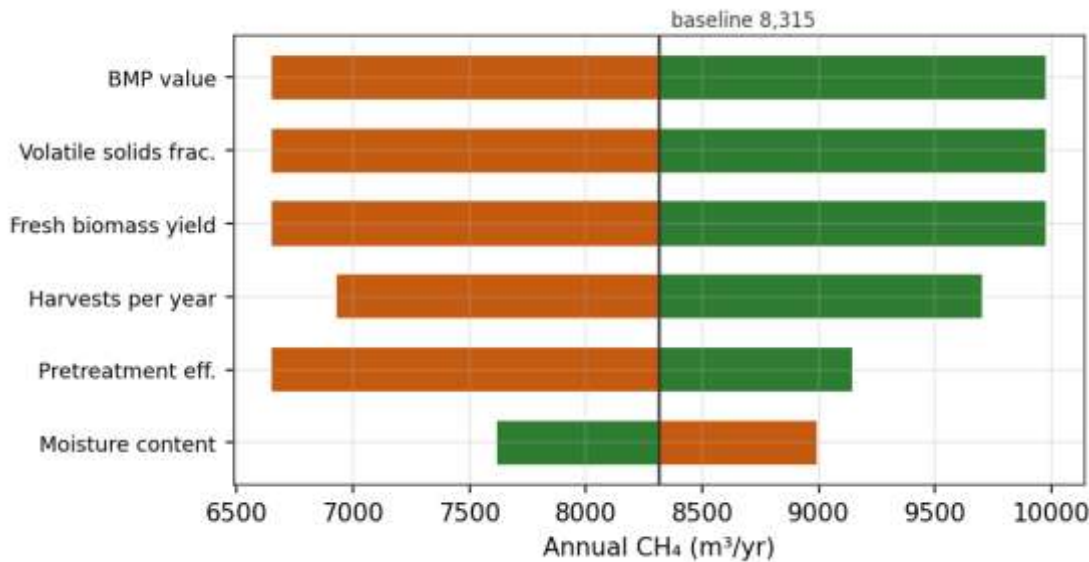


Fig. 10. Tornado plot: sensitivity of annual CH₄ to $\pm 20\%$ parameter variation.

Taken together, the experimental and calculated results confirm the central hypothesis: alkaline-pretreated 60-day Napier grass is a technically reliable, environmentally beneficial and economically viable feedstock for decentralised CBG production aligned with India's SATAT and GOBAR-Dhan missions, with biomass yield, methane potential and volatile-solids characterisation identified as the priorities for further optimisation.

V. CONCLUSION

This study establishes Napier grass as a highly productive feedstock for decentralised compressed biogas in the semi-arid irrigated regions of Maharashtra. Under a 60-day, six-harvest cycle, one acre yields 109.15 t fresh biomass, 31.00 t dry matter and 26.23 t volatile solids per year. The 60-day maturity stage offers the most balanced biochemical condition — 71.6% moisture, 84.6% volatile solids and a C/N ratio of 23.4 — and, when treated with 2% NaOH, achieves the highest methane yield of 317 mL CH₄/g VS, a 35.5% improvement over untreated biomass that demonstrates the effectiveness of mild alkaline pretreatment in disrupting lignocellulosic resistance. At field scale, the model delivers 8,315 m³ CH₄ per acre annually, upgradeable to 9,077 m³ of IS 16087:2018-grade CBG at 91.6% methane purity and equivalent to 297,677 MJ (about 82,688 kWh). It avoids roughly 26.5 t CO₂e, produces 16.57 t of FCO-compliant digestate, and yields a gross profit near ₹3.10 lakh per acre per year, providing a strong foundation for the system's energy, environmental and economic merits. Future work should advance to Phase-II pilot-scale validation under real field conditions, examine year-round co-digestion with municipal wet waste, quantify purification, compression, storage and transport costs, and use GIS-based site selection to guide the placement of decentralised CBG plants across Maharashtra — thereby converting waste into wealth in a genuinely circular, low-carbon energy system.

REFERENCES

1. F. A. F. Antunes, L. C. Thomé, J. C. Santos, et al., "Multi-scale study of the integrated use of carbohydrate fractions of sugarcane bagasse for ethanol and xylitol production," *Renewable Energy*, vol. 163, pp. 1343–1355, 2021.
2. A. M. Buswell and H. F. Mueller, "Mechanism of methane fermentation," *Industrial & Engineering Chemistry*, vol. 44, no. 3, pp. 550–552, 1952.
3. M. Chanpla, P. Kullavanijaya, A. Janejadkarn, and O. Chavalparit, "Effect of harvesting age and performance evaluation on biogasification from Napier grass in separated stages process," *KSCE J. Civ. Eng.*, vol. 22, no. 1, pp. 40–45, 2018.
4. S. O. Dahunsi, "Mechanical pretreatment of lignocelluloses for enhanced biogas production: Methane yield prediction from biomass structural components," *Bioresource Technology*, vol. 280, pp. 18–26, 2019.
5. C. Herrmann, M. Heiermann, and C. Idler, "Effects of ensiling, silage additives and storage period on methane formation of biogas crops," *Bioresource Technology*, vol. 102, no. 8, pp. 5153–5161, 2011.
6. V. C. Igbokwe, F. N. Ezugworie, C. O. Onwosi, G. O. Aliyu, and C. J. Obi, "Biochemical biorefinery: A low-cost and non-waste concept for promoting sustainable circular bioeconomy," *J. Environ. Manage.*, vol. 305, 114333, 2022.
7. M. K. Jameel, M. A. Mustafa, H. S. Ahmed, et al., "Biogas: Production, properties, applications, economic and challenges — A review," *Results in Chemistry*, vol. 7, 101549, 2024.
8. A. E. Jonathan, G. K. Agbajor, O. O. David, et al., "Determination and prediction of biogas production potential from selected biomasses in Sapele, Nigeria," *Renewable Energy*, vol. 255, 123802, 2025.
9. J. A. Kriswantoro, K.-Y. Pan, and C.-Y. Chu, "Co-digestion approach for enhancement of biogas production by mixture of untreated Napier grass and industrial hydrolyzed food waste," *Front. Bioeng. Biotechnol.*, vol. 11, 1269727, 2024.
10. N. A. Kubde, N. P. Gulhane, J. Taler, and D. Taler, "A comparative study between conventional and advanced biomass pretreatment methods applied on Napier grass," *Cleaner Eng. Technol.*, vol. 17, 100694, 2023.
11. A. Kumar and S. Banerjee, "Thermal valorisation of biomass: gasification and pyrolysis routes to biochar, bio-oil and syngas," *Renewable Sustainable Energy Rev.*, 2021.
12. E. Lewin, J. Clifton-Brown, E. Magenau, et al., "Biogas potential of *Sida hermaphrodita* compared with silage maize and cup plant," *GCB Bioenergy*, vol. 16, no. 8, e13149, 2024.
13. P. Pomdaeng, C.-Y. Chu, K. Sripraphaa, and H. Sintuya, "An accelerated approach of biogas production through a two-stage BioH₂/CH₄ continuous anaerobic digestion system from Napier grass," *Bioresource Technology*, vol. 361, 127709, 2022.
14. M. S. Reza, S. Afroze, M. S. A. Bakar, et al., "Biochar characterization of invasive *Pennisetum purpureum* grass: Effect of pyrolysis temperature," *Biochar*, vol. 2, no. 2, pp. 239–251, 2020.
15. J. R. D. A. S. D. C. Rocha, J. C. Machado, P. C. S. Carneiro, et al., "Elephant grass ecotypes for bioenergy production via direct combustion of biomass," *Ind. Crops Prod.*, vol. 95, pp. 27–32, 2017.
16. A. Saravanan, "Biomass conversion technologies for a circular bioeconomy: thermochemical and biochemical routes — a review," 2025.
17. I. Siegert and C. Banks, "The effect of volatile fatty acid additions on the anaerobic digestion of cellulose and glucose in batch reactors," *Process Biochemistry*, vol. 40, no. 11, pp. 3412–3418, 2005.
18. D. Singh and S. Chakrabarti, "Compressed biogas (CBG) in India: technological options, challenges and prospects," review article, 2023.
19. J. M. Triolo, S. G. Sommer, H. B. Møller, M. R. Weisbjerg, and X. Y. Jiang, "A new algorithm to characterize biodegradability of biomass during anaerobic digestion: Influence of lignin concentration on methane production potential," *Bioresource Technology*, vol. 102, no. 20, pp. 9395–9402, 2011.
20. W. Wilawan, P. Pholchan, and P. Aggarangsi, "Biogas production from co-digestion of *Pennisetum purpureum* cv. Pakchong 1 grass and layer chicken manure using a completely stirred tank," *Energy Procedia*, vol. 52, pp. 216–222, 2014.