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Optimisation of Biogas Production from Co-Digestion of Organic Waste Streams of Kolhapur Municipal Corporation Using Response Surface Methodology

Prakash Lagamavar, Sudhir B. Desai, Mrunalini P. Jagtap
Yashwantrao Chavan School of Rural Development
Shivaji University, Kolhapur, Maharashtra
✉ prakash@srigrowgas.com
✉ desaisudhirb@gmail.com
✉ powar.mrunalini4@gmail.com

ABSTRACT

Kolhapur Municipal Corporation (KMC) generates approximately 488 tonnes of municipal solid waste daily, of which nearly 57% is biodegradable organic matter presently disposed of without energy recovery. This study characterises five major organic waste streams of KMC — food waste, vegetable market waste, fruit market waste, cattle dung, and slaughterhouse waste — and optimises their co-digestion ratio using Response Surface Methodology (RSM) with a D-optimal mixture design. Individual substrate characterisation revealed complementary carbon-to-nitrogen (C/N) profiles, motivating a co-digestion strategy. A 38-run mixture design was executed in bench-scale CSTR digesters, yielding a statistically significant model ($F = 48.52$, $R^2 = 0.981$). The optimised blend — 40% food waste, 25% vegetable waste, 20% fruit waste, 10% cattle dung and 5% slaughterhouse waste — achieved a C/N ratio of 24.8:1 and a specific biogas yield of 724 mL/g VS, validated experimentally within 1% of the model prediction. A conceptual 200 MT/day plant based on this formulation shows techno-economic viability (IRR 18.4%, payback period 6.8 years). The findings demonstrate that systematic co-digestion optimisation, grounded in a rigorous waste characterisation and experimental design methodology, can substantially improve biogas recovery from municipal organic waste in Tier-2 Indian cities.

KEYWORDS *: Anaerobic co-digestion; Biogas; Municipal solid waste; Response Surface Methodology; Kolhapur*

NOMENCLATURE

AD	Anaerobic Digestion
BMP	Biochemical Methane Potential
CD	Cattle Dung
COD	Chemical Oxygen Demand
CSTR	Continuously Stirred Tank Reactor
C/N	Carbon-to-Nitrogen Ratio
FAN	Free Ammonia Nitrogen
FCO	Fertiliser Control Order
FOS/TAC	Volatile Acids to Alkalinity Ratio
FrMW	Fruit Market Waste
FW	Food Waste
HRT	Hydraulic Retention Time
IRR	Internal Rate of Return
ISR	Inoculum-to-Substrate Ratio
KMC	Kolhapur Municipal Corporation
MSW	Municipal Solid Waste
NPV	Net Present Value
OLR	Organic Loading Rate
RSM	Response Surface Methodology
SHW	Slaughterhouse Waste
TS	Total Solids
VFA	Volatile Fatty Acids
VMW	Vegetable Market Waste
VS	Volatile Solids

INTRODUCTION

Municipal solid waste (MSW) generation has grown steadily worldwide with urbanisation, and Indian cities are witnessing a particularly sharp rise, with national MSW generation projected to increase substantially over the coming decade as urban population expands [13]. In response, the Government of India has promoted several waste-to-energy initiatives, including the GOBARdhan (Galvanising Organic Bio-Agro Resources Dhan) scheme and the SATAT (Sustainable Alternative Towards Affordable Transportation) initiative, both aimed at converting organic waste and cattle dung into compressed biogas (CBG) and organic manure under the National Bioenergy Programme [14, 25]. Despite this policy push, conversion infrastructure at the municipal level remains limited in most Tier-2 cities, and a large share of biodegradable waste continues to be transported to open dumping grounds without energy recovery.

Kolhapur Municipal Corporation (KMC), a Class-A civic body serving approximately 6.5 lakh residents across 76 administrative wards spanning 67.77 km^2, generates about 488 MT of solid waste per day, of which nearly 57% (roughly 278 MT/day) is biodegradable organic matter [27]. At present this fraction is collected and transported to the Kasaba Bawada disposal site with limited energy recovery, representing a significant lost opportunity for renewable energy generation and organic fertiliser production.

Anaerobic digestion (AD) is a biologically mediated, four-stage process — hydrolysis, acidogenesis, acetogenesis and methanogenesis — through which complex organic polymers are sequentially broken down by consortia of bacteria and archaea into biogas, typically comprising 50–70% methane (CH_4) and 30–45% carbon dioxide (CO_2) with trace hydrogen sulphide (H_2S) and moisture [22]. The residual digestate, rich in nitrogen, phosphorus and potassium, can be mechanically separated into solid and liquid fractions and applied as organic fertiliser, closing the nutrient loop between urban waste generation and peri-urban agriculture [23].

Mono-digestion of a single waste stream is, however, frequently unstable because individual streams rarely possess a carbon-to-nitrogen (C/N) ratio in the optimal range of 20–30:1 required for balanced microbial activity: nitrogen-rich streams risk ammonia inhibition, while carbon-rich streams digest slowly and yield poorly [8, 17]. Co-digestion of complementary waste streams is widely reported to overcome this limitation by diluting inhibitory compounds, balancing nutrients and improving buffering capacity [4].

The objectives of this study are to: (i) characterise the physico-chemical properties of the five principal organic waste streams generated within KMC; (ii) determine their individual biogas yield potential through biochemical methane potential (BMP) assays; (iii) screen two-substrate combinations to identify synergistic pairings; (iv) statistically optimise a five-substrate co-digestion recipe using Response Surface Methodology (RSM) to maximise specific biogas yield; and (v) evaluate the conceptual plant design and techno-economic feasibility of a full-scale facility based on the optimised formulation.

LITERATURE REVIEW

Global Studies on Anaerobic Co-Digestion of Municipal Organic Waste

Elango et al. [1] investigated biogas production from MSW combined with domestic sewage in a batch digester operated at 26–36 °C with a fixed hydraulic retention time (HRT) of 25 days, and reported a maximum yield of 0.36 m^3/kg VS at an optimum organic feeding rate of 2.9 kg VS/m^3/day, alongside 87.6% total solids reduction. Mata-Alvarez et al. [4], in a meta-analysis of over 1,200 co-digestion studies published between 2010 and 2013, confirmed that blending complementary substrates generally improves methane yield relative to mono-digestion through nutrient balance and dilution of inhibitory compounds. Bouallagui et al. [5] found that combining vegetable market waste with cattle dung at a 3:1 ratio improved the blended C/N ratio to 22.5:1 and raised biogas yield to 0.41 m^3/kg VS, while Wan Azlina and Idris [2] demonstrated that leachate chemical oxygen demand (COD) strength strongly influences biogas production kinetics in MSW leachate co-digestion. Pavi et al. [7] demonstrated that co-digesting the organic fraction of MSW with fruit and vegetable waste at an optimal ratio of 1:3 increased methane yield by 141% relative to mono-digestion of MSW alone, achieving 396.6 mL

CH_4/g VS — consistent with the broader finding that food-waste-rich blends are among the most readily biodegradable co-digestion feedstocks [24]. Pognani et al. [10] and Scaglia et al. [11] separately reported that substituting energy crops with the organic fraction of MSW in full-scale digesters did not compromise specific biogas yield, while Abad et al. [12] showed that characterising the biogas potential of multiple industrial waste streams enables cost-optimised co-digestion recipes in a circular-economy framework.

Co-Digestion Studies and Policy Context in India

Singh et al. [6], working with waste from the Azadpur mandi in Delhi — Asia's largest wholesale fruit and vegetable market — reported that a 2:1 vegetable-waste-to-cattle-dung ratio improved specific yield to 0.58 m^3/kg VS. Rajendran et al. [15] reviewed household-scale biogas digesters across developing countries and highlighted that feedstock variability, rather than digester design, is frequently the dominant constraint on performance in decentralised Indian systems. Kondusamy and Kalamdhad [16] reviewed pre-treatment strategies for food waste digestion and noted that Indian food waste, owing to its high oil and salt content relative to Western counterparts, often requires blending with a buffering co-substrate such as cattle dung or agricultural residue to sustain stable methanogenesis. At the policy level, the Ministry of New and Renewable Energy's National Bioenergy Programme and the GOBARdhan scheme [14, 25] provide capital subsidy and viability-gap-funding mechanisms for municipal biomethanation and CBG projects, but implementation has been constrained in Tier-2 cities by the absence of locally validated feedstock-blending protocols — a gap this study addresses directly for Kolhapur.

Process Inhibition, C/N Ratio and Ammonia Toxicity

Yeniğün and Demirel [8] established that free ammonia nitrogen (FAN) concentrations above 100–200 mg/L are strongly inhibitory to methanogenic activity, a finding directly relevant to managing nitrogen-rich streams such as slaughterhouse waste. Chen et al. [17], in a widely cited review of anaerobic digestion inhibition mechanisms, catalogued ammonia, volatile fatty acid (VFA) accumulation, sulphide, and light metal ions as the principal inhibitors of methanogens, and emphasised that co-digestion is among the most effective strategies for diluting any single inhibitor below its threshold concentration. Khalid et al. [26] similarly concluded, in a review of solid-waste anaerobic digestion, that blending nitrogen-rich and carbon-rich substrates to approach a C/N ratio of 20–30:1 is the single most consistent predictor of stable, high-yield digestion across the studies they surveyed.

Statistical Optimisation of Anaerobic Digestion Using RSM

Response Surface Methodology is a collection of statistical and mathematical techniques for developing, improving and optimising processes in which a response of interest is influenced by several variables, and is particularly suited to mixture problems where components must sum to a fixed total [21]. Karthik Rajendran et al. [3] applied a techno-economic simulation framework to biogas production from the organic fraction of MSW and demonstrated that systematic scenario optimisation, rather than fixed design heuristics, materially improves both yield and project economics. While RSM and related design-of-experiments approaches are well established in bioprocess and wastewater engineering, their application to multi-substrate co-digestion of Indian municipal waste streams specifically remains limited in the published literature.

Research Gap

Despite this substantial literature base, no published study has systematically characterised the full set of organic waste streams generated in a Tier-2 Indian city and optimised their co-digestion ratio using a rigorous statistical mixture-design framework validated through both batch and semi-continuous trials, and further extended into a conceptual plant design with techno-economic assessment. This study addresses that gap for Kolhapur Municipal Corporation, and proposes a methodology that is directly transferable to comparable Indian cities.

METHODOLOGY

Study Area and Waste Sampling Protocol

Five organic waste streams generated within KMC were selected for study on the basis of their contribution to total organic waste tonnage: food waste (FW) from hotels, messes and households; vegetable market waste

(VMW) from the Mahadwar Road, Rajarampuri and Shahupuri market clusters; fruit market waste (FrMW) from the wholesale fruit market and five associated retail clusters; cattle dung (CD) from four dairy cooperatives and two goshalas within KMC limits; and slaughterhouse waste (SHW) from the KMC-operated municipal slaughterhouse. Representative composite samples of each stream (approximately 5 kg per sample) were collected weekly over a twelve-week period spanning two seasons — monsoon (July–September) and winter (January–March) — to capture seasonal variability in waste composition. Samples were manually sorted to remove inert and non-biodegradable contraries, size-reduced to a nominal particle size of below 10 mm using a laboratory shredder, homogenised, and either analysed within 48 hours of collection or stored at 4 °C to minimise pre-analysis biodegradation.

Analytical Methods and Standard Protocols

Each waste stream was characterised for total solids (TS), volatile solids (VS), C/N ratio, pH and chemical oxygen demand (COD) in triplicate, using the standard methods summarised in Table 1. TS and VS were determined gravimetrically by oven-drying at 105 °C to constant weight followed by ashing at 550 °C, per APHA Standard Methods [20]. Total organic carbon and total Kjeldahl nitrogen were determined using a CHNS elemental analyser and the Kjeldahl digestion-distillation method respectively, from which the C/N ratio was calculated. pH was measured using a calibrated bench-top pH meter on a 1:10 (w/v) aqueous extract, and COD was determined by the closed reflux titrimetric method.

Table 1: Analytical parameters and standard methods used for waste characterisation

Parameter	Method / Standard	Instrument
TS, VS	Gravimetric (105 °C / 550 °C) – APHA 2540 B, E	Hot-air oven, muffle furnace
C/N ratio	CHNS analysis + Kjeldahl digestion	CHNS elemental analyser
pH	Electrometric, 1:10 (w/v) extract	Digital pH meter
COD	Closed reflux titrimetric – APHA 5220 C	COD digester, titration
VFA, Alkalinity	Titrimetric (Nordmann method)	Auto-titrator
Biogas composition	Gas chromatography (TCD/FID)	Portable biogas analyser / GC

Biochemical Methane Potential (BMP) Assay

The biogas yield potential of each individual substrate was determined using a batch BMP assay adapted from the protocol of Angelidaki et al. [18] and VDI 4630 [19]. Anaerobic sludge from an operating digester, acclimatised for two weeks prior to use, served as inoculum. Batch reactors (500 mL serum bottles, 400 mL working volume) were charged with substrate and inoculum at an inoculum-to-substrate ratio (ISR) of 2:1 on a VS basis, flushed with nitrogen gas to establish anaerobic headspace conditions, sealed, and incubated at 35 ± 1 °C in a temperature-controlled shaking incubator for up to 30 days, or until daily gas production fell below 1% of the cumulative volume. Biogas volume was measured daily by water displacement, and composition (%CH_4, %CO_2) was determined every three days by gas chromatography. Inoculum-only blanks were run in parallel and subtracted from substrate assay values to correct for endogenous gas production. All assays were conducted in triplicate, and results are expressed as mL CH_4/g VS added.

Screening of Two-Substrate Combinations

Prior to the full mixture-design experiment, all ten possible two-substrate combinations of the five waste streams were screened at two mixing ratios each in bench-scale 5 L borosilicate CSTR digesters (3 L working volume, 35 ± 1 °C mesophilic, low-speed continuous mixing), with biogas volume measured by water displacement over a 30-day batch cycle. A synergy index, defined as the ratio of the observed biogas yield of the blend to the VS-weighted theoretical yield of its components in isolation, was used to rank combinations and shortlist the most promising pairings for inclusion in the multi-substrate optimisation.

Experimental Design for Co-Digestion Optimisation (RSM)

A D-optimal mixture design was constructed in Design-Expert® v13 (Stat-Ease Inc.) to optimise the proportion of each of the five substrates, expressed as a fraction of

total VS subject to a sum-to-100% mixture constraint: FW (X_1: 20–60%), VMW (X_2: 10–35%), FrMW (X_3: 5–30%), CD (X_4: 5–25%), and SHW (X_5: 2–15%). The design comprised 38 experimental runs, including model points, five centre-point replicates for pure-error estimation, and additional lack-of-fit points, generated to support fitting of a special-cubic mixture polynomial of the general form:

$$Y = \Sigma\beta_i X_i + \Sigma\Sigma\beta_{ij} X_i X_j + \Sigma\Sigma\Sigma\beta_{ijk} X_i X_j X_k$$

where Y is the predicted response (specific biogas yield or methane content), X_i are the substrate proportions, and β terms are the linear, quadratic and special-cubic mixture coefficients estimated by least-squares regression. Each of the 38 runs was conducted in triplicate in the bench-scale CSTR digesters described in Section 3.4, with total biogas yield and methane content recorded as the two response variables. Model adequacy was assessed using analysis of variance (ANOVA), the lack-of-fit test, the coefficient of determination (R^2), adjusted R^2, predicted R^2, and the adequate precision ratio, which is recommended to exceed 4 for a model to be considered suitable for navigating the design space. The optimum blend was identified using a numerical desirability function (Derringer and Suich approach), which simultaneously maximises specific biogas yield and methane content subject to the mixture constraint, and the model-predicted optimum was subsequently validated by independent triplicate experimental runs at the identified blend ratio.

Semi-Continuous Digester Operation and Process Monitoring

Following identification of the optimum blend, a bench-scale CSTR (5 L total, 3 L working volume) was operated in semi-continuous (fed-batch) mode for 30 days at the design organic loading rate (OLR) and hydraulic retention time (HRT) derived from separate single-factor trials (Section 4.5); OLR and HRT are widely recognised as the two operating parameters with the greatest influence on digester stability and specific yield [9]. The digester was fed once daily, with an equal volume of digestate withdrawn prior to each feeding to maintain constant working volume. Process performance was monitored through daily biogas volume measurement, gas composition analysis by gas chromatography every three days, daily pH measurement, and the ratio of volatile organic acids to total inorganic carbonate (FOS/TAC), determined twice weekly by the Nordmann titration method. Free ammonia nitrogen was calculated from total ammoniacal nitrogen, pH and temperature using the Anthonisen equation. The digester was considered to have reached steady state when daily biogas yield varied by less than 10% over three consecutive HRTs.

Digestate Quality Assessment

Digestate from the semi-continuous trial was mechanically separated into solid and liquid fractions using a screw-press separator. The solid fraction was analysed for total Kjeldahl nitrogen (Kjeldahl method), P_2O_5 (vanadomolybdate spectrophotometric method), K_2O (flame photometry), moisture content, pH, and faecal coliform count (most-probable-number method), and assessed against the Fertiliser Control Order (FCO) 1985, Schedule VI specifications for organic fertilisers [23].

Conceptual Plant Design and Mass Balance

A conceptual biogas plant was sized on a design basis of 200 MT/day of organic waste input, corresponding to approximately 72–80% of KMC's estimated recoverable organic waste after accounting for collection efficiency and seasonal variability. Digester working volume was computed from the design OLR and the daily VS loading implied by 200 MT/day of the optimised blend, and distributed across four CSTR digesters of nominal 2,250 m^3 each, sized to standard fabrication modules and configured to allow one unit to be taken offline for maintenance without halting plant operation. Gross biogas production was extrapolated from the bench-scale specific yield with a conservative scale-up de-rating factor applied. Two downstream gas utilisation pathways were considered: combined heat and power (CHP) generation for electricity export, or upgrading to compressed biogas (CBG) via water-scrubbing or pressure-swing adsorption; the plant layout was conceived to accommodate either. Digestate management comprises windrow composting of the solid fraction (30–45 days) to produce a stabilised biofertiliser, with the liquid fraction partly recirculated as process dilution water and the remainder distributed to farmers.

Techno-Economic Analysis Methodology

Capital cost (CAPEX) was estimated using a bottom-up approach comprising civil works (digesters, tanks, foundations), mechanical equipment (mixers, pumps, gas holders, and the CHP or upgrading skid), electrical and instrumentation systems, and land and balance-of-plant infrastructure, benchmarked against typical per-tonne installed-capacity costs reported for Indian biomethanation projects. Operating cost (OPEX) components included manpower, purchased power, maintenance, chemicals and consumables, and digestate handling. Revenue streams considered were power or CBG sales, biofertiliser sales, and avoided tipping/disposal cost. Financial performance was evaluated using discounted cash flow (DCF) analysis over a 25-year project life at a 12% discount rate, representative of the cost of capital for Indian municipal infrastructure projects, from which net present value (NPV), internal rate of return (IRR) and simple payback period were derived. A one-at-a-time sensitivity analysis was performed on capital cost, feedstock/tipping cost, and power or CBG selling price to test the robustness of the computed IRR to input uncertainty.

4. RESULTS AND DISCUSSION

Waste Stream Characterisation

Individual substrate characterisation (Table 2) showed FW and VMW to be nitrogen-rich, with C/N ratios of 13.7 and 15.3 respectively; SHW was extremely nitrogen-rich (C/N = 5.9); while FrMW and CD were closer to the optimal 20–30:1 range (C/N = 26.2 and 27.0 respectively). This spread of C/N ratios across the five streams is precisely the condition under which co-digestion is expected to outperform mono-digestion of any single stream [4, 26].

Table 2: Physico-chemical characteristics and specific BMP of individual waste streams

Waste Stream	VS (%)	C/N Ratio	BMP (mL CH_4/g VS)
Food Waste	24.3	13.7	612
Vegetable Mkt. Waste	14.1	15.3	480
Fruit Mkt. Waste	17.2	26.2	525
Cattle Dung	16.7	27.0	310
Slaughterhouse Waste	29.5	5.9	485

Individual Substrate BMP and Two-Substrate Screening

BMP assays (Figure 1) ranked FW highest (612 mL CH_4/g VS), followed by FrMW (525) and SHW (485), with CD lowest (310 mL CH_4/g VS) owing to its already rumen-digested, recalcitrant fibre content — though CD remained valuable for its buffering capacity rather than its yield contribution. Screening trials identified FW combined with CD (50:50) as the strongest two-substrate synergy, improving yield by 14.8% over the weighted average of the components, consistent with the buffering mechanism described by Chen et al. [17]. Combinations exceeding 15% SHW consistently exhibited ammonia accumulation during screening, consistent with the inhibition threshold reported by Yeniğün and Demirel [8].

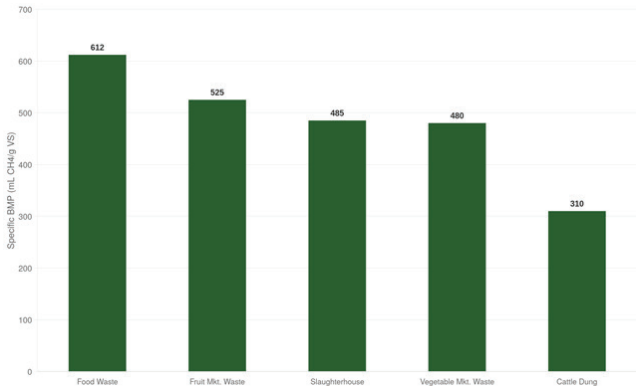


Fig. 1: Specific biochemical methane potential (BMP) of individual waste streams

RSM Model Fitting and Statistical Validation

The mixture-design model fitted to the 38 experimental runs was highly significant ($F = 48.52$, $p < 0.0001$) with $R^2 = 0.981$ and a non-significant lack-of-fit ($p = 0.184$), indicating excellent agreement between predicted and observed responses across the design space; the adequate precision ratio exceeded the recommended threshold of 4, confirming the model's suitability for navigating the mixture space. Biogas yield across the 38 runs ranged from 508–724 mL/g VS. Ranked by standardised coefficient, FrMW (+4.82) and FW (+3.95) contributed most positively to yield, VMW (+2.18) and CD (+0.86) contributed moderately, while SHW (−1.24)

had a negative effect beyond its optimum proportion, reflecting ammonia toxicity at higher inclusion levels consistent with Section 2.3.

Response Surface Optimisation and Validation

Applying the desirability function to the fitted model identified an optimum blend of 40% FW, 25% VMW, 20% FrMW, 10% CD and 5% SHW (by VS), achieving a blended C/N ratio of 24.8:1 — within the ideal 20–30:1 range — and a predicted biogas yield of 718 mL/g VS. Independent triplicate validation trials at this composition produced 724 ± 18 mL/g VS (within 1% of the model prediction) with a methane content of 63.4%, corresponding to a specific methane yield of approximately 459 mL CH_4/g VS. Table 3 benchmarks this result against comparable co-digestion studies from the literature, showing that the five-substrate optimised blend exceeds the yields reported for simpler two- or three-substrate combinations, supporting the conclusion that multi-substrate RSM optimisation captures synergies beyond what pairwise blending alone achieves.

Table 3: Comparison of this study's optimised co-digestion yield with published co-digestion studies

Study / Substrate Combination	Blending Ratio	Yield
Elango et al. [1] – MSW + sewage	Single-factor OLR optimum	0.36 m³ biogas/ kg VS
Bouallagui et al. [5] – VMW + CD	3:1	0.41 m³ biogas/ kg VS
Singh et al. [6] – VMW + CD (Azadpur)	2:1	0.58 m³ biogas/ kg VS
Pavi et al. [7] – OFMSW + fruit/ veg. waste	1:3	396.6 mL CH_4/g VS
This study – FW + VMW + FrMW + CD + SHW	40:25:20:10:5	459 mL CH_4/g VS (724 mL biogas/g VS)

Process Stability at Design OLR and HRT

Single-factor trials on the optimised blend identified an optimum OLR of 3.0 g VS/L·day, beyond which yield declined progressively (Figure 2), and an optimum HRT of 20 days, achieving 78.4% VS removal with diminishing returns at longer retention (Figure 3). A 30-day semi-continuous trial at this operating point (Table 4) showed the FOS/TAC ratio decline from 0.28 to 0.14 and free ammonia nitrogen remain at 42–51 mg N/L, both within stable operating ranges and well below the 100–200 mg N/L inhibition threshold reported by Yeniğün and Demirel [8] — confirming that the optimised blend avoids the ammonia accumulation risk associated with SHW-rich mixtures identified during screening.

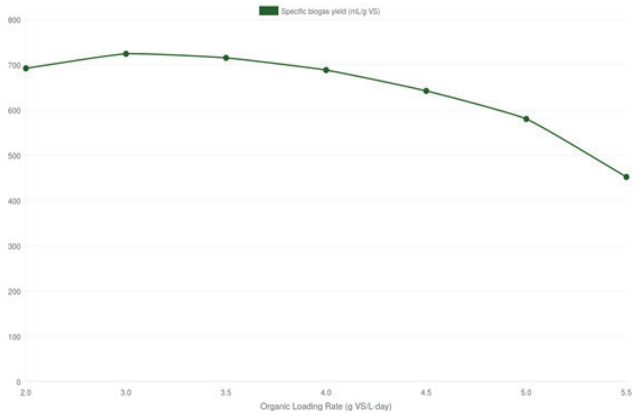


Fig. 2: Effect of organic loading rate (OLR) on specific biogas yield

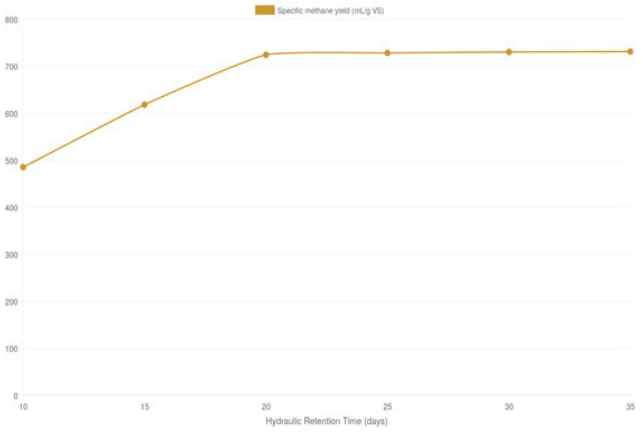


Fig. 3: Effect of hydraulic retention time (HRT) on specific methane yield

Digestate Quality

The digestate solid fraction met FCO (1985) Schedule VI biofertiliser standards for total nitrogen (4.62% dry wt.), P_2O_5 (1.68% dry wt.) and faecal coliform count, adding further value as an organic manure by-product and supporting a secondary revenue stream for the proposed plant.

Conceptual Plant Design and Techno-Economic Feasibility

Table 4 summarises the resulting plant design and techno-economic indicators for a conceptual 200 MT/day facility based on the optimised formulation. The projected internal rate of return comfortably exceeds the 10–12% cost of capital typical of Indian municipal infrastructure projects, and one-at-a-time sensitivity analysis indicated that the IRR remained above the cost-of-capital threshold across the tested range of capital cost and feedstock/tipping cost variation, indicating the project's economics are not narrowly dependent on any single favourable assumption.

Table 4: Process operating parameters and techno-economic indicators (200 MT/day plant)

Parameter	Value
Optimum OLR	3.0 g VS/L·day
Optimum HRT (VS removal)	20 days (78.4%)
Digester configuration	4 × 2,250 m³ CSTR
Gross biogas production	~27,100 m³/day
Net exportable power	~2.4 MWe
Capital cost	~Rs. 78.84 crore
Simple payback period	6.8 years
Internal rate of return (IRR)	18.4%
Discount rate used for NPV/IRR	12% over 25-year life

CONCLUSIONS

The principal contribution of this study is methodological: characterising KMC's organic waste as five distinct streams, rather than a single undifferentiated fraction, and combining a structured screening-then-optimisation experimental pipeline with RSM, exposed complementary C/N and biodegradability profiles that mono-digestion studies cannot capture. The resulting yield gain over comparable two-substrate co-digestion reported in the literature (Table 3) suggests that multi-substrate RSM optimisation captures synergies that pairwise blending misses — particularly the buffering role of cattle dung and the under-recognised yield contribution of fruit market waste. Because the operating envelope and economic outcome reported here were derived from the same waste-characterisation-to-optimisation pipeline, described in full in Section 3, the approach is directly transferable to other Indian Tier-2 cities with similarly mixed organic waste streams, offering a template for evidence-based biogas plant design in place of generic loading assumptions.

The principal limitation of this study is that its findings rest on bench-scale batch and semi-continuous trials; pilot-scale continuous validation at a scale intermediate between the bench and the proposed 200 MT/day facility remains necessary before full-scale deployment. Future work should additionally examine pre-treatment of the lignocellulosic fraction of vegetable market waste to further improve yield, agronomic field trials of the resulting digestate on local soils, and a comparative assessment of centralised versus decentralised plant configurations for KMC's ward-level waste collection network.

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