

Review Paper on Ecofriendly Temple Waste Management: an Integrated Process for Methane Biofuel and Organic Fertilizer Production at Sangli, Maharashtra

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Abstract - Temple waste — predominantly composed of floral offerings such as marigold (*Tagetes erecta*), aster (*Callistephus chinensis*), and basil leaves (*Ocimum sanctum*) — constitutes a substantial but chronically under-managed organic resource at holy places across India. Conventional disposal through river immersion or open landfilling leads to greenhouse gas emissions, groundwater contamination, and aesthetic degradation of sacred sites. This review critically examines the scientific and techno-economic feasibility of an integrated valorisation pathway that transforms temple waste into two commercially valuable outputs: methane-rich biogas and nutrient-dense organic fertilizer (digestate). Drawing upon experimental evidence from anaerobic digestion studies conducted at analogous sites in Maharashtra, we evaluate the impact of alkaline chemical pretreatment (sodium carbonate and sodium bicarbonate), solar-assisted digester heating, and co-digestion with canteen food waste on methane yields. Key findings indicate that Na_2CO_3 pretreatment improves biogas output by up to 106% and reduces chemical cost by 96% relative to NaOH ; solar heating amplifies yield by a further 122%; and 30% food-waste co-digestion adds 32.6% incremental gain. The raw biogas methane content reaches 57.52%, surpassing previous floral-waste studies. Downstream purification of hydrogen sulfide using zero-valent iron (Fe^0) and activated carbon packed-bed adsorbers is reviewed, alongside CO_2 removal technologies — water scrubbing, membrane separation, pressure-swing adsorption, chemical absorption, and emerging electrochemical separation — that upgrade the biomethane to near-pipeline quality. The organic digestate is characterised for nitrogen, phosphorus, and potassium content, confirming suitability as a biofertilizer. Microbial fuel cell (MFC) as an alternative bioelectricity pathway is also assessed. This review concludes that a decentralised, solar-integrated biogas plant co-located with temple premises in Sangli offers a socially

acceptable, financially viable, and environmentally sound circular-economy solution for sacred-site waste management.

Key Words: *Anaerobic digestion; Temple floral waste; Biogas; Alkaline pretreatment; Solar digester heating; Co-digestion; Hydrogen sulfide removal; Biogas upgrading; Organic fertilizer; Circular economy*

1. INTRODUCTION

India is home to over one million temples, mosques, churches, and other places of worship, many of which attract tens of thousands of devotees daily. The Vitthal Rukmini Temple at Pandharpur, the Mahalaxmi Temple at Kolhapur, and numerous shrines in the Sangli district of Maharashtra represent iconic examples where floral offerings are made round-the-clock. Fresh flowers — chiefly marigold, aster, rose, nishigandha, and shevanti — alongside tulsi (basil) leaves and other organic materials, are offered in large volumes and then discarded within 24 to 48 hours. Municipal surveys suggest that temple-dense cities like Sangli generate several tonnes of such waste per day.

The conventional fate of this waste is environmentally destructive. Floral debris is routinely immersed in the Krishna and Warna rivers that flow through Sangli, contributing to biochemical oxygen demand (BOD) loading, algal blooms, and the suppression of aquatic biodiversity. Alternatively, it is collected with municipal solid waste (MSW) and landfilled, where anaerobic decomposition in open dumps generates methane — a greenhouse gas with a global warming potential (GWP) 25 times that of CO_2 on a 100-year horizon — and leachate that contaminates groundwater.

Yet this same floral waste possesses physico-chemical properties that make it a promising feedstock for anaerobic digestion (AD). Its carbon-to-nitrogen (C:N) ratio of approximately 21:1 falls within the optimal range of 20:1 to 30:1 for methanogenesis. Its high moisture content (75–80%) facilitates slurry preparation, and its

organic carbon content ($\approx 48\%$) translates into substantial methane potential. Prior studies have confirmed methane fractions of 44–57% in biogas derived from temple floral waste, comparable to or better than conventional feedstocks such as cattle dung.

Despite this potential, the deployment of biogas technology at Indian temples remains minimal. India's total biogas production stands at approximately 2.07 billion m^3 per year — a tiny fraction of its estimated potential of 29–48 billion m^3 per year. Barriers include lack of awareness, insufficient pretreatment knowledge, capital cost, and perceived operational complexity. The present review addresses these barriers by systematically synthesising the experimental literature on temple waste valorisation, with particular emphasis on integrated process design appropriate for the Sangli context.

The review is structured as follows: Section 2 characterises the temple waste resource at Sangli. Section 3 reviews pretreatment strategies. Section 4 discusses anaerobic digestion design and performance. Section 5 covers biogas purification including H_2S removal and CO_2 separation/upgrading. Section 6 assesses organic fertilizer potential. Section 7 examines alternative bioelectricity pathways via microbial fuel cells. Section 8 presents a techno-economic and environmental assessment. Section 9 proposes an integrated process flowsheet for Sangli. Section 10 concludes with research gaps and future directions.

2. TEMPLE WASTE RESOURCE CHARACTERISATION AT SANGLI

2.1 Quantity and Composition

Sangli city in Maharashtra hosts several prominent temples along the banks of the Krishna River. A conservative estimate, extrapolated from field surveys at analogous temple-dense cities, suggests a daily floral waste generation of 3–8 tonnes (fresh weight) from the major shrines in Sangli alone. During festivals such as Ganesh Chaturthi, Diwali, and Dussehra, daily generation can spike 5–10-fold. The dominant floral components are marigold (*Tagetes erecta*) and aster (*Callistephus chinensis*), which together typically constitute 60–70% of the waste by mass.

Laboratory analysis of dried and ground floral waste from the Vitthal Rukmini Temple (Pandharpur, Maharashtra) reported the following proximate characteristics: moisture content 75–80% (fresh basis), organic carbon 48.32%, total nitrogen 2.32%, crude fat 0.43%, and a C:N ratio of 21:1. These values confirm excellent suitability for anaerobic digestion, since a C:N

ratio in the range of 20–30:1 is widely recognised as optimal for methanogenesis.

2.2 Physico-Chemical Properties and Lignocellulosic Content

Fresh, untreated flowers cannot produce biogas directly — a finding replicated consistently across multiple independent experimental studies. The structural barrier is lignocellulosic in nature: the plant cell walls of marigold and aster contain cellulose (35–45%), hemicellulose (20–30%), and lignin (10–18%), which physically encapsulate the fermentable carbohydrates and prevent enzymatic access. Drying reduces the moisture content, making mechanical pretreatment (crushing/grinding) feasible, while chemical pretreatment disrupts the lignin-carbohydrate ester bonds, increases internal surface area and porosity, and ultimately improves biodegradability.

Table 1: Physico-chemical characteristics of floral waste relevant to anaerobic digestion

Parameter	Marigold	Aster	Optimal AD Range
Moisture content (%)	75–80	76–82	80–95
Organic carbon (%)	47–50	46–49	> 30
Total nitrogen (%)	2.1–2.5	2.0–2.4	> 0.5
C:N ratio	20–22	20–23	20–30
Crude fat (%)	0.4–0.5	0.3–0.5	< 5
pH (fresh slurry)	5.8–6.2	5.6–6.0	6.5–7.5
Volatile solids (% of TS)	88–92	86–90	> 70

Sources: Kulkarni & Ghanegaonkar (2019); Singh et al. (2007); Singh & Bajpai (2011)

3. PRETREATMENT STRATEGIES FOR FLORAL WASTE

3.1 Physical Pretreatment

Physical pretreatment typically involves two sequential operations: (i) solar or oven drying to reduce moisture to manageable levels and (ii) mechanical size reduction by manual or hand-operated crushing/grinding. Drying reduces the fresh-basis moisture content from 75–80% to below 15%, enabling efficient mechanical comminution. Smaller particle sizes (< 5 mm) present a greater surface area for enzymatic and microbial attack during digestion. Experimental evidence confirms that drying and mechanical pretreatment alone are insufficient to initiate biogas production from floral waste — chemical pretreatment is mandatory as an additional step. Nonetheless, the physical pretreatment is a necessary precondition for effective chemical pretreatment, as it ensures homogeneous chemical penetration.

The use of a hand-operated crushing device — rather than electrically powered grinders — is particularly relevant in the Sangli context, since it eliminates dependency on grid electricity for the pretreatment step, reduces operational costs, and makes the technology accessible to temple trusts with limited technical capacity.

3.2 Chemical Pretreatment: Mechanisms and Agent Selection

Alkaline chemical pretreatment is the most effective established approach for enhancing biodegradability of lignocellulosic materials. The mechanism involves saponification and cleavage of ester bonds between hemicellulose and lignin, swelling of the cellulose structure, reduction in crystallinity and degree of polymerisation, and an increase in the internal surface area and porosity of the biomass.

Sodium hydroxide (NaOH) has been the conventional reference chemical for alkaline pretreatment of floral waste, with an optimum dose of 40 g NaOH per kg of dried aster flowers and 80 g NaOH per kg of dried marigold. However, NaOH is highly corrosive, poses occupational health hazards, is expensive, and its caustic nature complicates safe handling by non-technical temple staff.

A landmark innovation by Kulkarni & Ghanegaonkar (2019) demonstrated that sodium carbonate (Na_2CO_3) and sodium bicarbonate (NaHCO_3) can be substituted for NaOH with superior results. At a concentration of 0.16 g/g-T Na_2CO_3 , aster flowers yielded 84.86 N ml/g-TS of biogas — a 106.2% improvement over NaOH

pretreatment — while marigold yielded 100.40 N ml/g-TS (103.4% improvement). The chemical pretreatment cost per litre of biogas produced fell from \$0.011 to \$0.001 for aster (a 90.3% cost saving), and from \$0.018 to \$0.00066 for marigold (a 96.3% saving). Sodium carbonate is commercially available in local markets across India, costs a fraction of NaOH, and is substantially less hazardous.

Sodium bicarbonate (baking soda) at 0.16 g/g-TS yielded 101.8 N ml/g-TS of biogas from aster — slightly higher than the equivalent Na_2CO_3 dose — and can be considered the optimal chemical for settings where even greater user-friendliness is valued. The pretreatment protocol involves soaking dried and ground floral waste in the alkaline solution for 24 hours at ambient temperature in a separate container external to the digester.

3.3 Comparison with Other Substrates and Prior Studies

Prior to the Kulkarni & Ghanegaonkar (2019) study, calcium carbonate (CaCO_3) had been used as a pretreatment agent for temple waste (Singh & Bajpai, 2011), yielding methane content of 44–54% in seasonal operation. Singh et al. (2007) demonstrated using 6% NaOH that maximum biogas production from 120 g of pre-treated marigold, dhatura, ankra, rose, and bel leaves reached 12.9 L in a 1.5 L digester over 35 days. Ranjitha et al. (2014) established that withered flowers at 7% substrate concentration yielded an average of 16.69 g/kg of biogas in 4.5 days, outperforming all vegetable waste feedstocks tested.

4. ANAEROBIC DIGESTION: PROCESS DESIGN AND PERFORMANCE

4.1 Digester Configuration

Anaerobic digestion proceeds through four biochemical stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis. For temple waste, the floating drum digester (drum-in-drum type) has been established as the most suitable configuration for community-scale operation. Its advantages include: (i) simplicity of construction using polyethylene material; (ii) self-indicating biogas volume measurement via the rising gasholder; (iii) built-in stirring action through the up-and-down motion of the gasholder, which prevents scum formation; and (iv) portability that makes the units accessible to diverse installation sites.

Laboratory-scale experiments were conducted in floating drum digesters of 3.5 L and 5 L capacity, feeding

100–150 g of pre-treated floral waste per batch. Results were validated in a prototype digester of 230 L capacity equipped with an inbuilt stirrer and solar heating coil, fed with 350 g of dried temple waste daily. The prototype produced 628 L of biogas over 29 days of continuous operation — confirming scale-up validity.

4.2 Key Process Parameters

Total solids content in the digester slurry was maintained at 5–7% by mass. The inoculum (from an existing biogas plant) was added at 10% by volume to seed the digester with active anaerobic bacterial communities. A retention time of 22–31 days was observed for complete digestion of floral waste, shorter than the 35-day retention common for cattle dung digesters, reflecting the relatively labile nature of floral organic matter. The slurry pH ranged between 5.5–6.4 in the prototype digester — slightly below the optimal pH of 6.5–7.5 for methanogens. Biogas became flammable 6–8 days after startup.

4.3 Solar-Assisted Digester Heating

Temperature is arguably the most critical variable governing AD rate and methane yield. Mesophilic digestion (30–40°C) balances metabolic activity and operational stability, but ambient temperatures in Sangli during December–February can drop to 12–18°C — conditions that severely inhibit methanogenic activity. Solar heating of the digester addresses this seasonal constraint sustainably.

Experimental results using a solar water heater (flat-plate collector, 300 L/day capacity, output temperature ≈60°C) circulated through a galvanised iron coil embedded in the digester slurry demonstrated biogas yield improvements of 61.6–122.8% relative to ambient-temperature digesters. The maximum biogas production achieved with solar heating reached 149.26 Nml/g-TS of dried flower waste. The digester slurry temperature was maintained at 26–32°C even when the ambient minimum was 21–24°C.

4.4 Co-Digestion with Food Waste

Major temples and pilgrimage sites in the Sangli district operate large community kitchens (langar/bhandara) that generate substantial quantities of food waste. Co-digestion of aster flower waste with 10%, 20%, and 30% food waste (by mass) yielded biogas volumes of 100.6, 110.6, and 122.7 Nml/g-TS respectively, compared to 92.5 Nml/g-TS for 100% floral waste — representing improvements of 8.7%, 19.6%, and 32.6% respectively.

Table 2: Summary of biogas performance under different process enhancement strategies

Enhancement Strategy	Specific Yield (Nml/g-TS)	Improvement vs. Baseline	Reference
Baseline: NaOH pretreatment, ambient Temp.	41–49	—	Kulkarni & Ghanegaonkar (2019)
Na ₂ CO ₃ pretreatment (0.16 g/g-TS)	85–100	+103–106%	Kulkarni & Ghanegaonkar (2019)
NaHCO ₃ pretreatment (0.16 g/g-TS)	102	+107% (aster)	Kulkarni & Ghanegaonkar (2019)
Solar digester heating (50°C water bath)	149	+122%	Kulkarni & Ghanegaonkar (2019)
Co-digestion: 70% flower + 30% food waste	123	+32.6%	Kulkarni & Ghanegaonkar (2019)
Withered flowers (multiple genera)	~14.5 L/kg wet	Superior to vegetable waste	Ranjitha et al. (2014)

Nml/g-TS = normalised mL per gram of total solids

5. BIOGAS PURIFICATION AND UPGRADING

5.1 Raw Biogas Composition from Temple Waste

Gas chromatographic analysis of raw biogas from anaerobic digestion of alkaline-pretreated floral waste revealed the following composition: methane (CH₄) 57.52%, carbon dioxide (CO₂) 26.28%, with trace amounts of hydrogen sulfide (H₂S), water vapor, and nitrogen. This methane fraction exceeds that reported by Singh & Bajpai (2011) (44–54%), establishing the Na₂CO₃/NaHCO₃ pretreatment approach as a benchmark for floral waste digestion. At 57.52% CH₄, the raw biogas is directly usable for cooking via a modified LPG stove.

5.2 Hydrogen Sulfide Removal

H₂S is a toxic, corrosive contaminant present at concentrations of 50–10,000 ppm in raw biogas depending on feedstock composition. Two technologically mature approaches are particularly appropriate for the Sangli community-scale context:

Zero-Valent Iron (Fe⁰): Al Mamun & Torii (2015) demonstrated that Fe⁰ at 90% purity effectively removes H₂S from biogas through adsorption and chemical precipitation. With an average inlet H₂S concentration of 211 ppm, the maximum removal efficiency reached 95% at pH 6, yielding an outlet concentration below 10 ppm — well below the 50 ppm threshold acceptable for internal combustion engines. Using 10 g of Fe⁰ in a U-tube system at a biogas flow rate of 2.5 L/min, CH₄ concentration correspondingly increased to 77–78%.

Activated Carbon (AC) from Biomass Waste: Sawalha et al. (2020) demonstrated that locally synthesised AC from eucalyptus bark, almond shells, and coffee grains, activated with KOH, achieves H₂S adsorption capacities of up to 690 mg H₂S/g AC. In a packed-bed reactor with an inlet H₂S concentration of 970 ppm, 100% removal efficiency was maintained for 45 minutes at a 2 cm bed height. For Sangli, locally available agricultural residues (sugarcane bagasse, rice husk, or coconut shells) can substitute.

5.3 Carbon Dioxide Removal and Biogas Upgrading

CO₂ constitutes approximately 26–45% of raw biogas and significantly reduces its calorific value. Upgrading to biomethane (>96% CH₄) opens pathways to vehicular fuel use, pipeline injection, and higher-efficiency power generation. Five state-of-the-art CO₂ separation technologies are reviewed below:

- (i) **High-Pressure Water Scrubbing (HPWS):** Accounts for ~41% of global biogas upgrading plants. Based on the 24-fold higher CO₂ solubility in water compared to CH₄. Net energy requirement: 0.56 kWh/kg CO₂.
- (ii) **Pressure Swing Adsorption (PSA):** Selectively adsorbs CO₂ on zeolite or carbon-based adsorbents under 4–10 bar. Net energy: 0.58 kWh/kg CO₂. Maximum CH₄ yield of 91% demonstrated.
- (iii) **Membrane Separation (MS):** Net energy: 0.65 kWh/kg CO₂. Membrane lifetime of 5–10 years.
- (iv) **Chemical Absorption:** Amine scrubbing achieves >99% CH₄ recovery but has the highest net energy requirement (1.67 kWh/kg CO₂).
- (v) **Electrochemical CO₂ Separation:** An emerging technology achieving a minimum net energy requirement of 0.13 kWh/kg CO₂ — approximately half that of HPWS.

Table 3: Comparison of biogas upgrading technologies for temple waste biogas application

Technology	Net Energy (kWh/kg CO ₂)	CH ₄ Recovery (%)	Maturity	Suitability for Sangli
Water Scrubbing (HPWS)	0.56	> 97	Commercial	High, if water source available
Pressure Swing Adsorption	0.58	91–97	Commercial	High, modular, dry process
Membrane Separation	0.65	92–98	Commercial	Moderate, membrane replacement cost
Chemical Absorption (Amine)	1.67	> 99	Commercial	Low, high energy, complex operation
Electrochemical Separation	0.13–0.25	Developing	Bench scale	Future potential with solar PV

Source: Mohammadpour et al. (2024); Al Mamun & Torii (2015)

6. ORGANIC FERTILIZER (DIGESTATE) PRODUCTION AND CHARACTERISATION

The solid-liquid effluent remaining after AD — the digestate — is a nutrient-dense organic amendment with significant agronomic value. Laboratory analysis of the digested slurry from floral waste showed a total solids reduction of 77% during AD, from 3.2% organic carbon (inlet) to 0.75% (outlet) — confirming extensive mineralisation of organic carbon to biogas. Crucially, nitrogen content was retained (inlet 0.17%, outlet 0.12%), as was phosphorus and potassium, in plant-available inorganic forms.

Moqsud (2021) characterised the by-products of microbial fuel cells treating organic waste and found nitrogen (N) 1.5–1.7%, phosphorus (P) 0.6–0.8%, and potassium (K) 1.3–1.7% — values comparable to commercial composts. This places floral waste digestate firmly in the category of Class A biostimulants/biofertilisers suitable for agricultural application. The agricultural hinterland of the Sangli district — particularly the irrigated sugarcane, grape, and pomegranate belt along the Krishna River — represents a natural off-taker for digestate.

It is important to note that raw digestate from AD of floral waste should be pathogen-tested before agricultural application, particularly if co-digestion with food waste is practiced. Pasteurisation of the digestate at 70°C for one hour is a standard precautionary measure.

7. ALTERNATIVE PATHWAY: MICROBIAL FUEL CELLS FOR BIOELECTRICITY

The Microbial Fuel Cell (MFC) represents an alternative organic waste valorisation technology in which electroactive bacteria directly oxidise organic substrates at the anode to generate electricity, without intermediate biogas production. Moqsud (2021) evaluated single-chamber MFCs using various substrates. Cow dung produced the highest peak voltage (450 mV), followed by fruit waste (380 mV), chicken droppings (340 mV), rice bran (320 mV), food waste (300 mV), and leaf waste (300 mV).

The AD + biogas engine/CHP pathway is recommended as the primary energy recovery route for Sangli temples, given its higher energy output, established technology readiness, and compatibility with cooking fuel applications. MFC technology should be monitored for future deployment as power densities improve through nanotechnology-enhanced electrode materials and reactor optimisation.

8. TECHNO-ECONOMIC AND ENVIRONMENTAL ASSESSMENT

8.1 Energy Balance and Biogas Yield Estimation for Sangli

Assuming a conservative daily temple floral waste availability of 3,000 kg (fresh weight) in the Sangli district, with 25% solid content: 3,000 kg fresh waste × 0.25 (solid fraction) = 750 kg dry mass. At the experimentally validated yield of 100 Nml/g-TS (Na₂CO₃ pretreatment, solar heating), expected daily biogas production = 75 m³/day. Co-digestion with 30% food waste increases this by 32.6% to approximately 99

m³/day. At 57.52% methane content, the net daily methane production is approximately 57 m³/day, with an energy value of approximately 570 kWh/day. Operating a 25 kWe CHP unit at 35% electrical efficiency, the plant could generate approximately 200 kWh of electricity per day.

8.2 Economic Analysis

The dramatic 96% reduction in pretreatment chemical cost achieved by substituting Na₂CO₃ for NaOH is the single largest OPEX reduction opportunity identified in this review. At a current market price of approximately INR 20–25 per kg for Na₂CO₃ versus INR 300–400 per kg for industrial-grade NaOH, the daily chemical cost for a 750 kg dry-weight plant is approximately INR 1,800–3,200 — compared to INR 15,000–25,000 for equivalent NaOH dosage.

Revenue streams include: (i) savings on LPG/CNG currently purchased by temple kitchens; (ii) sale of excess electricity to the grid under Maharashtra net metering policies; (iii) sale of digestate as organic fertilizer at INR 3,000–5,000 per tonne; and (iv) potential carbon credits under Gold Standard or CDM methodology. A preliminary payback period of 4–6 years is estimated.

8.3 Environmental Impact Assessment

The primary environmental benefits include: (i) elimination of floral waste disposal into the Krishna River; (ii) displacement of fossil fuel-derived LPG for cooking — avoiding approximately 115 tonnes of CO₂ equivalent per year; (iii) prevention of open landfill methane emissions — methane GWP is 25× CO₂; and (iv) substitution of synthetic nitrogen fertilizer with biogenic digestate, reducing upstream CO₂ emissions from Haber-Bosch process ammonia synthesis. The integrated system qualifies as a circular bioeconomy model consistent with India's Nationally Determined Contributions under the Paris Agreement.

9. INTEGRATED PROCESS FLOWSHEET FOR SANGLI TEMPLE WASTE BIOGAS PLANT

Based on the synthesis of experimental evidence presented in this review, we propose the following integrated process design:

Stage 1 — Waste Collection and Sorting: Daily collection of floral waste from temple premises into segregated bins. Sorting to remove inorganic contaminants. Optional segregation of food waste from temple kitchens into a separate stream for co-feeding.

Stage 2 — Physical Pretreatment: Solar drying of flowers on open drying beds (1–2 days during dry season; forced-air drying during monsoon). Manual crushing/grinding to achieve particle size < 5 mm.

Stage 3 — Chemical Pretreatment: Soaking of dried and ground flowers in Na_2CO_3 solution (0.16 g/g-TS) for 24 hours at ambient temperature. Batch pretreatment in separate plastic containers external to the digester.

Stage 4 — Slurry Preparation and Feeding: Mixing pre-treated flowers with temple kitchen food waste (up to 30% by mass) and water to achieve 5–7% TS slurry. Daily batch feeding of the floating drum digester.

Stage 5 — Anaerobic Digestion: Floating drum polyethylene digesters (100–500 L capacity, scalable modular units). Solar water heater with coil heating system to maintain slurry temperature at 28–35°C year-round. Digester retention time: 22–28 days.

Stage 6 — Biogas Purification: H_2S removal: Fe0 U-tube scrubber (95% H_2S removal). Moisture removal: condensate trap on gas outlet pipe. CO_2 removal (optional): HPWS or PSA unit.

Stage 7 — Biogas Utilisation: Primary use: direct combustion for temple kitchen cooking. Secondary use: stationary biogas generator for temple electricity.

Stage 8 — Digestate Management: Effluent collected in lagoon or covered tank. Pasteurisation at 70°C for 1 hour. Compost-blending with dry agricultural waste. Distribution to local farmers as biofertiliser.

10. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite the promising experimental evidence reviewed, several significant knowledge gaps remain: (1) Long-term continuous operation studies in CSTR mode over 6–12 months. (2) Microbial community analysis using 16S rRNA amplicon sequencing or metagenomics. (3) Seasonal variability quantification at Sangli through a 12-month waste audit. (4) Techno-economic modelling with Monte Carlo analysis. (5) Digestate quality and safety: comprehensive heavy metal screening and pathogen enumeration. (6) H_2S and siloxane profiling across seasonal cycles. (7) Electrochemical CO_2 capture integration using solar PV. (8) Social acceptance and policy alignment through participatory research with Sangli temple trusts, municipal authorities, and farmers under the Swachh Bharat Mission and GOBAR-DHAN scheme frameworks.

11. CONCLUSIONS

This review has established that temple floral waste possesses excellent potential for integrated valorisation into methane biofuel and organic fertilizer at Sangli, Maharashtra. The key conclusions are:

1. Temple floral waste (marigold and aster) has a C:N ratio of 21:1, organic carbon content of 48.32%, and raw biogas methane content reaching 57.52% — superior to all prior floral waste digestion studies.
2. Alkaline pretreatment with Na_2CO_3 or NaHCO_3 at 0.16 g/g-TS achieves 103–106% improvement in biogas yield over NaOH pretreatment at 90–96% lower chemical cost.
3. Solar digester heating to 28–35°C increases biogas yield by up to 122% relative to ambient conditions, enabling stable year-round production.
4. Co-digestion with temple kitchen food waste (30% by mass) adds a further 32.6% to biogas output and improves process stability.
5. H_2S removal using zero-valent iron (95% efficiency) and KOH-activated biochar packed-bed adsorbers are technically viable, low-cost options for biogas purification.
6. Biogas upgrading to biomethane is achievable through water scrubbing or PSA (net energy 0.56–0.58 kWh/kg CO_2).
7. The organic digestate contains N, P, and K in ranges comparable to commercial composts, confirming its value as a biofertiliser for the Sangli agricultural region.
8. An integrated process combining Na_2CO_3 pretreatment, solar-heated floating drum digestion, co-digestion with food waste, Fe0 H_2S scrubbing, and digestate composting represents a technically sound, financially viable, and environmentally beneficial circular-economy solution. Implementation under the GOBAR-DHAN scheme with capital subsidy from the Ministry of New and Renewable Energy (MNRE) would significantly improve project economics.

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