Pak. j. sci. ind. res. Ser. A: phys. sci. 2025 **68A**(3) 304-313

Impact of High Calorific Value Biomass Substrate for High Yield of Biomethane

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(received April 30, 2025; revised June 13, 2025; accepted July 8, 2025)

Abstract. The global push towards sustainable energy solutions has intensified the exploration of biomass substrates for bio methane production. This study evaluates the biomethane potential of various organic wastes, including neem deoiled cake (NDC), mango kernel (MK), waste maize flour (WMF) and cow dung (CD), with a specific focus on their physico-chemical properties and calorific values. Among the tested substrates, NDC exhibited the highest calorific value at 5219 Kcal/Kg, followed by MK at 4932 Kcal/Kg, WMF at 4187 Kcal/Kg and CD at 1820 Kcal/Kg. NDC also demonstrated substantial total solids (TS: 92.5%) and volatile solids (VS: 84.7%), indicating its strong potential for enhanced biomethane yield. Key parameters such as pH, moisture content, ash content, total nitrogen and carbon-to-nitrogen (C:N) ratio were systematically characterized: NDC had a pH of 6.7, moisture content of 7.5%, ash content of 6.8%, total nitrogen of 4.2% and a C:N ratio of 23:1. MK showed a pH of 6.3, moisture content of 8.2%, ash content of 5.1%, total nitrogen of 2.9% and a C:N ratio of 30:1. WMF presented a pH of 6.5, moisture content of 10.4%, ash content of 4.7%, total nitrogen of 1.8% and a C:N ratio of 36:1. CD had a pH of 7.1, moisture content of 78.4%, ash content of 15.2%, total nitrogen of 1.4% and a C:N ratio of 19:1. Additionally, essential trace metals critical for microbial metabolism, such as iron (Fe), zinc (Zn) and copper (Cu), were detected in adequate concentrations, supporting efficient methane generation. The findings emphasize the significance of selecting high-energy, nutrient-rich biomass to optimize bio methane production, highlighting NDC and MK as particularly promising substrates for scalable renewable energy systems.

Keywords: bio-methane, high-calorific-value, biomass

Introduction

The climate crisis has strengthened the call to use sustainable and renewable energy resources. Among these renewable or sustainable alternative energy resources, biomethane is a promising and revolutionizing option. The utilization of high calorific value biomass substrates holds immense benefits of biomethane. Biomethane is a purified form of biogas mainly composed of methane which has gained significance as an eco-friendly alternative to conventional fossil fuels (Dębowski *et al*., 2020). In the process of biomethane, the impact of high-energy biomass substrates has been a pivotal area of research due to an anticipated potential of increasing productivity and efficiency (Deheri and Acharya, 2022). The calorific value of biomass varies based on the type of biomass being considered. The calorific value is the total amount of energy obtained from a substance. It is denoted in kilojoules per kilogram (KJ/Kg) or megajoules per kilogram (MJ/Kg) which shows the amount of heat released when a certain amount of biomass is burnt. This value is different based on the substance, the moisture content, variety or composition (Dębowski *et al*., 2020). In case of higher moisture, the calorific value is usually lower as during combustion, some energy evapourates water (Dragusanu *et al*., 2022). Sustainable waste management is another global concern which implies the adoption of methods which can generate energy out of the waste (Esteban-Lustres *et al*., 2022). Moreover, it calls for capitalizing on energy resources which are cheaper than fossil fuels from the disposal of lignocellulosic waste while harnessing its energy content (Lee *et al*., 2020).

(Olatunji *et al*., 2023) addressed the challenges associated with lignocellulosic materials like *Arachis hypogea* shells during anaerobic digestion and employed thermal

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pretreatment before the digestion process. Varying temperatures, such as 90 °C, 100 °C, 110 °C and 120 °C, were used for the substrate for durations of 30 and 60 min. These substrates underwent digestion at mesophilic temperature for 30 days in a batch digester. For physico-chemical analyses, scanning electron microscopy (SEM), X-ray diffraction (XRD) and Fourier transform infrared spectroscopy (FTIR) were conducted. The analysis revealed that there was an enhanced porosity with increased temperature and time, while XRD analysis indicated a reduction in the crystalline index, supporting the breakdown of the crystalline structure. Similarly, FTIR analysis depicted the elimination of hemicellulose and lignin. The highest biomethane yield, increased by 23.96%, was observed at 100 °C for 30 min. Temperatures exceeding this threshold led to a decreased biomethane yield, ranging between 16% and 44%. The findings of the study concluded that through conventional thermal pretreatment at 100 °C for 30 min, there was an optimal improvement in biomethane yield during the anaerobic digestion of *Arachis hypogea* shells which is viable for commercial use (Olatunji *et al*., 2023). Dębowski *et al*. (2020) evaluated the effect of using microalgae biomass from *Arthrospira platensis* and *Platymonas sub cordiformis* in common agricultural biogas plant feedstock (i.e., cattle manure, maize silage) on methane production. Anaerobic bio degradability tests were conducted using respirometry reactors with initial organic loading rates, temperatures and retention times set at 5.0 Kg VS/m^3, 35 °C and 20 days, respectively. A systematic increase in biogas production efficiency was observed as the proportion of microalgae biomass in the feedstock rose from 0% to 40% (%VS) (Dębowski *et al*., 2020).

(Souvannasouk *et al*., 2021) conducted an experiment on Napier grass and cattle slurry-based biogas production. This experimental study evaluated the impact of feedstock screening on biogas yield from Napier grass and cattle slurry under mesophilic conditions in batch digesters. According to the results, the highest methane content was 64.4% and combining Napier grass with common cow farm slurry increased reaction rates, efficiency and methane content (Souvannasouk *et al*., 2021). Biomethane, a renewable and sustainable energy source, is produced through anaerobic digestion (AD) of organic materials, offering an environmentally friendly alternative to conventional fossil fuels. As concerns over climate change intensify, the demand for clean energy solutions has surged and biomethane production has emerged as a promising strategy to reduce greenhouse gas emissions, while addressing waste management challenges. Biomethane production primarily involves the breakdown of complex organic substrates by microbial communities under anaerobic conditions, which generates biogas composed predominantly of methane (CH_4) and carbon dioxide (CO_2). Among the factors influencing biomethane production, the type and quality of the feedstock, particularly its calorific value, play a pivotal role.

The calorific value of biomass refers to the amount of energy that can be obtained from its combustion, typically measured in terms of MJ/Kg or Kcal/Kg. Biomass with a higher calorific value generally contains more energy rich organic compounds, such as lipids, proteins and complex carbohydrates. These organic components, when subjected to anaerobic digestion which are converted into biogas. High calorific value (HCV) substrates are expected to yield higher amounts of methane per unit mass of feedstock, making them an attractive option for enhancing biomethane production.

Several studies examined biomass substrates for high yield of biomethane a gap persists to conduct a comprehensive optimization of pretreatment techniques, evaluations on long-term stability and efficiency, exploration of novel biomass substrates, integration of multiple feedstocks and rigorous techno-economic and environmental assessments. Enhancing bio-methane yields through the use of high-calorific-value biomass substrates presents a promising strategy for improving the efficiency and sustainability of anaerobic digestion processes. By integrating biomass sources with higher energy content, such as agricultural residues, food waste and energy crops, it is possible to significantly increase methane production, while optimizing the utilization of available resources. The careful selection and pretreatment of these substrates can further accelerate biodegradation rates and enhance the microbial activity within anaerobic digesters, leading to more robust and efficient biogas production systems. However, challenges remain in terms of substrate variability, process stability and optimizing the balance between high calorific value and digestibility. Future research should focus on refining pretreatment technologies, improving microbial consortia and exploring the synergistic effects of mixed substrates to maximize bio-methane output. As the global demand for renewable energy and waste-to-energy technologies continues to rise, the utilization of high-calorific-value biomass substrates in biogas production has the potential to play a key role in the transition to a more sustainable and circular bioeconomy. The present study depends on biofuel and bioenergy to address the challenge of accelerating renewable energy resources as well as highlights the critical role of advanced bio-based solutions in mitigating environmental challenges while meeting escalating energy demands.

Materials and Methods

Sample collection. Four biomass substrates were selected for this study due to their high calorific value and local availability. Neem kernel de-oiled cake (NKDC) was sourced from a nearby oil pressing mill, where neem oil was mechanically extracted. Ripe mango seeds were collected from a mango pulp processing unit; the seeds were separated and the kernels were retained as highlighted in Fig. 1. Waste maize flour (WMF), a by-product of flour milling, was obtained from local flour mills. Additionally, fresh cow dung (CD) was collected from a cattle colony to serve as both an inoculum and co-digestion material in the anaerobic digestion process.

Sample preparation. Each substrate underwent specific preparation procedures to ensure uniform particle size and enhanced digestibility. Neem seeds were first de-hulled to extract the kernels, which were then processed in an oil expeller to produce neem kernel de-oiled cake. Mango seeds were manually split to retrieve the kernels,

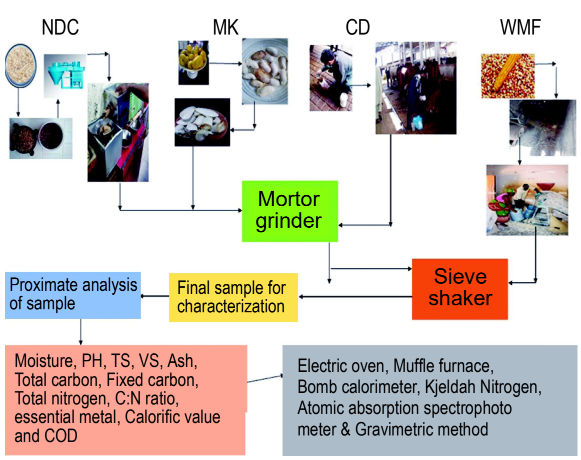

Fig. 1. Methodology for use of different biomass on physiochemical parameters of biomethane production.

which were air-dried before further processing. The maize flour waste was sieved to eliminate coarse impurities. All substrates were subsequently crushed or ground using a mechanical grinder and passed through sieves to achieve a consistent particle size suitable for anaerobic digestion trials. The prepared biomass materials were stored in airtight containers at ambient conditions until further use in experimental assays.

Analysis. To evaluate the biomethane potential of the selected biomass substrates, comprehensive physico-chemical analyses were performed. Parameters such as pH, moisture content, odour and colour were initially assessed to determine the general characteristics and stability of the samples. Key compositional metrics, including total solids (TS), volatile solids (VS), fixed carbon, total carbon and chemical oxygen demand (COD) were measured to estimate the organic load and degradability of each substrate. The carbon-to-nitrogen (C:N) ratio was also calculated, as it plays a critical role in microbial activity during anaerobic digestion. Additionally, proximate analysis included determination of moisture and ash content along with total nitrogen concentration. The calorific value of each biomass type was measured to assess its energy potential. Furthermore, essential trace metals such as ferric (Fe), zinc (Zn), copper (Cu), manganese (Mn) and boron (B) were quantified, as they influence enzymatic functions and microbial metabolism during the anaerobic digestion process.

Physico-chemical characterization. The substrates were analyzed for their basic physical parameters, including moisture content, colour, odour and pH. Moisture content was determined by using the oven-drying method at 105 °C until a constant weight was achieved. Colour and odour were recorded through visual and sensory observations, respectively and pH was measured by preparing a 10% slurry of each sample in distilled water and using a calibrated digital pH meter.

Proximate and ultimate analysis. Standard analytical procedures were followed to determine total solids (TS), volatile solids (VS), ash and fixed carbon content. TS and VS were measured using gravimetric analysis as per APHA guidelines. Ash content was estimated by combusting the sample in a muffle furnace at 550 °C. Fixed carbon was calculated as the residue after subtracting volatile and ash content. Total carbon and total nitrogen contents were measured using a CHNS analyzer. The carbon to nitrogen (C:N) ratio was calculated accordingly.

Calorific value and COD. The calorific value of each substrate was determined using a bomb calorimeter, which provides the energy content in Kcal/Kg. Chemical oxygen demand (COD) was assessed using the closed reflux titrimetric method (as per APHA standards), which estimates the amount of oxygen required to oxidize organic matter in the substrate.

Essential metal analysis. Concentrations of zinc (Zn), copper (Cu), iron (Fe), manganese (Mn) and boron (B) were determined using atomic absorption spectroscopy (AAS). For this, samples were digested using nitric-perchloric acid digestion and then analyzed to quantify the essential trace elements crucial for anaerobic digestion.

Results and Discussion

Effect of different substrates on physiochemical analysis. The biomethane potential of the selected substrates-neem deoiled cake (NDC), mango kernel (MK), waste maize flour (WMF) and cow dung (CD)- was assessed based on various physico-chemical parameters. Among the substrates, WMF exhibited the highest total solids (97.4%) followed by NDC (94.7%) and MK (91.4%), indicating a high concentration of organic matter available for anaerobic digestion. CD had significantly lower total solids (17.22%), as expected due to their high moisture content. In terms of volatile solids, which reflect the biodegradable portion, WMF (83.24%) and MK (81.58%) showed superior potential over NDC (73.6%) and CD (73.61%). The ash content was lowest in NDC (5.9%), suggesting minimal inorganic residue post-digestion, while CD had the highest ash (16.39%), likely due to undigested fibers and soil contamination. Fixed carbon content was notably higher in NDC (20.5%), indicating a substantial portion of non-volatile organic matter, which could contribute to sustained biogas production over time.

From a biochemical perspective as highlighted in Table 1, total carbon content was fairly consistent across all substrates, with CD showing the highest (45.93%) and NDC the lowest (42.0%). However, nitrogen content varied significantly, with NDC containing the highest (3.5%) and MK the lowest (1.0%). Consequently, the C:N ratio - a key factor influencing microbial activity and methane yield which was most balanced in NDC (12:1), close to the optimal range (20-30:1). MK and WMF showed elevated C:N ratios (44:1 and 35:1, respectively), suggesting a potential need for co-digestion with nitrogen-rich materials to optimize microbial metabolism. Calorific values further supported the energy potential, with NDC leading (5219 Kcal/Kg), followed by MK (4210 Kcal/Kg), WMF (3610 Kcal/Kg) and CD (3000 Kcal/Kg). Despite CD's high COD value (7560 mg/Kg), its lower calorific value and higher moisture may limit its standalone efficiency, making it more suitable as a co-substrate. Overall, NDC emerged as the most promising feedstock for high yield biomethane production, due to its balanced C:N ratio, high calorific value and favorable solid content.

Effect of physio-chemical analysis on use of different biomass for biomethane production. The physical characteristics of the substrates reveal distinct differences that influence their suitability for biomethane production. Neem deoiled cake (NDC) exhibited the lowest moisture content (5.3%), making it highly concentrated in dry matter and ideal for energy-dense bioconversion. In contrast, cow dung (CD) showed extremely high moisture (82.78%), indicating the need for dewatering or mixing with drier substrates for efficient digestion. WMF and MK had intermediate moisture levels (2.6%

Table 1. Effect of different biomass substrate on physicochemical characteristics

Biomethane potential analysis	Neem kernel deoiled cake (NDC)	Mango kernel (MK)	Waste maize flour (WMF)	Cow dung (CW)
Total solids %	94.7±2.45	91.4±2.26	97.4±2.22	17.22±0.92
Total volatile solids %	73.6±3.26	81.58±2.80	83.24±1.79	73.61±3.33
Ash %	5.9±0.10	12.42±1.11	11.76±1.61	16.39±0.01
Fixed carbon%	20.5±0.18	6.0±0.07	5.0±0.5	10.0±0.01
Total carbon %	42.0±2.75	44.8±1.92	45.7±1.68	45.93±1.39
Total nitrogen %	3.5±0.05	1.0±0.01	1.3±0.06	2.3±0.06
Carbon to nitrogen ratio C:N	12:1	44:1	35:1	20:1
Calorific value Kcal/Kg	5219±110.0	4210±70.0	3610±46.0	3000±59.0
COD mg/Kg	5355±112.0	3480±79.0	3600±60.0	7560±98.0

and 8.6%, respectively), also favouring efficient energy extraction. In terms of sensory characteristics, NDC had a bitter odour and brown to black color, whereas MK and WMF emitted a sweet, slightly earthy smell, which may suggest lesser microbial decomposition at the collection stage. CD was characterized by a strong foul smell, typical of active microbial activity. The pH values ranged from slightly acidic in MK (5.0) and WMF (5.6) to near neutral in NDC (7.4) and CD (7.2), with the latter two being more favourable for methanogenic bacteria that thrive in neutral conditions.

The analysis of essential metals highlights NDC as the richest in micronutrients vital for anaerobic digestion as given in Table 2. It had significantly higher concentrations of zinc (57 mg/Kg), copper (16.2 mg/Kg), iron (640 mg/Kg), manganese (33.6 mg/Kg) and boron (15.82 mg/Kg) compared to the other substrates. These trace elements play crucial roles as enzymatic cofactors, enhancing microbial metabolism and methane production. In contrast, MK and WMF were considerably deficient, with boron not detected and very low levels of other metals, which may limit their independent use unless supplemented. CD had moderate levels of zinc (36.8 mg/Kg) and copper (11.7 mg/Kg) but extremely low iron (1.2 mg/Kg), which is atypical given its origin from herbivorous waste. Overall, NDC not only offers favourable physical properties but also provides a rich micronutrient profile, making it an excellent standalone or co-substrate for enhanced bio methanation.

Effect of different biomass on calorfic value. The comparison of calorific values among neem kernel deoiled cake (NDC), mango kernel (MK), waste maize flour (WMF) and cow dung (CD) reflects significant differences in their energy potential as highlighted in Fig. 2. NDC exhibits the highest calorific value at 5219 kca/Kg, followed by MK with 4210 kca/Kg and WMF with 3610 kca/Kg. Cow dung has the lowest calorific value at 3000 kca/Kg. These variations underscore the varying suitability of these materials for energy generation purposes, with NDC being the most energetically potent and CD being the least, highlighting the importance of selecting appropriate biomass sources based on their calorific values for efficient energy production processes Fig. 2.

The significant advancements have been made in between 2021 and 2023, enhancing biomethane production through the integration of high calorific

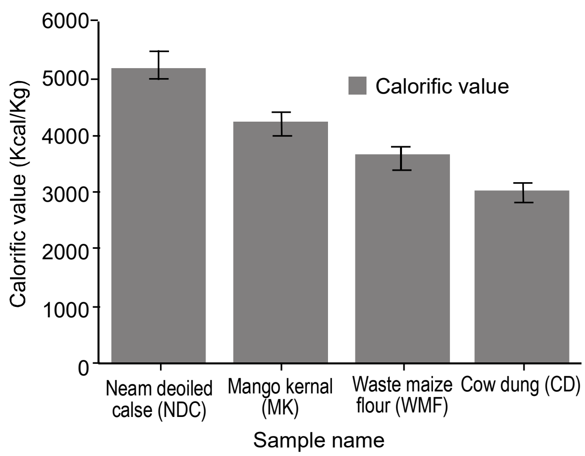

Fig. 2. Effect of different biomass on calorifc value.

Table 2. Effect of different biomass for biomethane production

S. No.	Neem deoiled cake (NDC)	Mango kernel (MK)	Waste maize flour (WMF)	Cow dung (CW)
		Physical		
Moisture %	5.3	8.6	2.6	82.78
Colour	Brown to black	Yellowish brown	Yellow	Greenish brown
Odour	Bitter	Sweet with slightly earthy	Sweet with slightly earthy	Strong foul smell
pH	7.4	5.0	5.6	7.2
		Essential metals		
Zinc mg/Kg	57	5.6	1.40	36.8
Cu mg/Kg	16.2	8.6	2.0	11.7
Fe mg/Kg	640	12.4	46.6	1.2
Manganese mg/Kg	33.6	0.03	3.3	8.7
Boron mg/Kg	15.82	Not detected	Not detected	4.5

value biomass substrates and advanced pretreatment and purification techniques. Studies have explored the use of municipal solid waste, agricultural residues (such as corn stover and sugarcane trash) and kitchen waste, often combined with materials like biochar, activated carbon or alkaline extracts, to improve anaerobic digestion efficiency. Innovations like hydrothermal depolymerization, ultrasonic treatments and novel systems such as the cryogenic temperature condensation system (CTCS) have been employed to boost biomethane yield and gas purity. Additionally, geographic information system (GIS) tools and land use efficiency indices have helped identify optimal locations for biogas production, supporting regional strategies for sustainable energy generation these all parameters described by different authors i.e. (Shanthi *et al*., 2023; Bianco *et al*., 2022; Deheri and Acharya, 2022; Djalma *et al*., 2022; Esteban *et al*., 2022; Glivin *et al*., 2022; Götze *et al*., 2022; Mohanakrishna *et al*., 2022; Pappalardo *et al*., 2022; Papurello *et al*., 2022; Rajneesh *et al*., 2022; Salehiyoun *et al*., 2022; Siegrist *et al*., 2022; Yao *et al*., 2022; Muhammad *et al*., 2021; Piechota, 2021).

Various pretreatment strategies have shown enhanced methane yields, with studies highlighting the importance of carefully controlled conditions - such as temperature, pressure and chemical dosage for optimal outcomes shown in Table 3.

Despite these advances, challenges remain in terms of feedstock heterogeneity, economic feasibility and scalability. High initial costs, energy demands and technical limitations have hindered the industrial adoption of many laboratory-scale innovations. Nonetheless, integrating advanced pretreatment methods into existing anaerobic digestion infrastructure and adopting efficient purification systems like CTCS offer promising pathways forward. Regional planning based on GIS data and land use analysis, as well as sustainable waste management practices using submerged anaerobic membrane bioreactors (SAnMBR) and livestock manure these are key strategies to reduce reliance on fossil fuels. Together, these developments underscore the potential of biomethane technologies in supporting energy independence and environmental sustainability, provided that economic and technical barriers are addressed through targeted policy and investment.

Future perspectives and advancements. Despite the numerous challenges, the future of biomethane production from waste maize flour, deoiled cake, cow dung and fruit pits is promising, with technological advancements, policy support and research initiatives opening new avenues for efficiency and scalability. One of the most significant breakthroughs in addressing feedstock biodegradability issues is the advancement of pre-treatment technologies such as hydrothermal carbonization, enzymatic hydrolysis and microwave assisted digestion, which can enhance the breakdown of lignocellulosic biomass (e.g. fruit pits) and improve methane yields. Additionally, co-digestion strategies, where multiple feedstocks are combined to balance carbon-to-nitrogen ratios and optimize microbial activity, offer a practical solution. For example, mixing waste maize flour (high in starch) with cow dung (rich in microbes and buffering agents) can stabilize digestion and prevent acidification, leading to higher biomethane yields. Similarly, blending deoiled cake with manure can mitigate ammonia inhibition while improving biogas production. Advances in metagenomic and microbial engineering techniques also present opportunities to enhance methanogenic pathways, enabling microbes to break down complex organic structures more efficiently. These synthetic biology approaches, combined with optimized reactor designs, such as high-rate digesters and anaerobic membrane bioreactors, could significantly improve methane production efficiency and reduce retention times.

On the economic and policy front, increased government incentives, carbon credit schemes and waste valorization initiatives are driving the commercialization of biomethane production from agricultural residues and food waste. Many countries are now mandating organic waste separation and offering feed-in tariffs for biogas-to-grid injection, creating a more favorable economic landscape. Additionally, decentralized biogas plants in rural areas are emerging as a viable solution to manage agricultural waste locally while generating off-grid renewable energy. The integration of biomethane into existing natural gas networks, along with advancements in bio-compressed natural gas (Bio-CNG) for transport, is further enhancing its economic viability. In the long term, power-to-methane (PtM) technologies, which combine renewable hydrogen with CO_2 from biogas plants, could revolutionize the industry by boosting methane yields and enabling carbon-neutral fuel production. Furthermore, circular bioeconomy models, where digestate from biomethane plants is processed into organic fertilizers, biochar, or high-value bioproducts, could create additional revenue streams and enhance sustainability. Overall, while challenges remain, the increasing adoption of advanced processing

Table 3. Summary of the studies for review

Resource material	Parameter	Key finding	Reference
High organic fraction loads of municipal solid waste + bio char	Controlled acidification, reduce VS, short hydraulic retention time, apply integration of gasification and dry anaerobic digestion technique.	Improved yield of biomethane (upto 36.6%).	(Salehiyoun *et al*., 2022)
Sugar can trash and diesel	Compared study between liquefied biomethane (LBM) and diesel used in Sao Paulo State.	Replace diesel used within 50% the state usage of biogas produced by sugarcane mills and landfill sites is beneficial transport sector of state.	(Djalma *et al*., 2022)
Geographic information system-based methods were made to identify appropriate place for biogas to be made.	Techno-spatial assessment which was checked for Switzerland.	The natural production potentials of electricity, heat, biogas and biomethane was made with the help of location- allocation algorithm and to obtain accuracy of greenhouse gas emissions from biomass transport.	(Siegrist *et al*., 2022)
Co-digested of waste (food+ cow)and use both extracts of CaO_2+$CaCO_3$ and NaOH for biohythane production	To check purifying efficiency at different chemical extract use in column and check gas flow rate.	Raised the levels hydrogen 97.85% at NaOH scrubber and methane up to 98.39% of comparison with water scrubber.	(Deheri *et al*., 2022)
Ashes from local wood boilers and activated carbon use by dry anaerobic digestion.	To remove sulphur and carbon dioxide and feasibility study on pilot scale.	To upgrade biogas to biomethane carried experiments on pilot plant scale by dry anaerobic digestion with absorbent material remove toxicity with retention time 95 h.	(Papurello *et al*., 2022).
Hazel nut shell	Hydrothermal at mesophilic, ultrasonic-hydrothermal treatment and oluble chemical oxygen demand	0.325 KWh Kg/*v/s* bio-methane was increased from co- digested Hazel nut shell valorization ultrasonic–hydrothermal	(Bianco *et al*., 2022)
Cow dung, kitchen dump and fiber reinforced plastic material for construction.	Mesophilic and thermophilic temperature, different pH	The non-corrosive and no effect on bio methane.	(Glivin *et al*. 2022)
Landfill gas 27.3 and 35.9 °C, cryogenic temperature condensation system CTCS	Volatile methyl siloxane(organic and inorganic) CTCS conditioned at 27 °C	Present study proposes CTCS as an alternative to technologies based on adsorption and absorption to remove siloxine at low temp., purify and upgrade biogas into biomethane.	(Piechota *et al*., 2021).
Lignocellulose biomass multi-layer high nutrient value and high density	High temperature and pressure, anaerobic digestion	Fast and highest produce bioenergy(H_2+CH_4) to valorize biomass by AD process	(Mohanakrishna *et al*., 2022).

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Resource material	Parameter	Key finding	Reference
Agro-industrial biomass, animal herds	Land use efficiency (LUE) index for southern Italy.	Calculated and estimated purpose the environmental sustainability of the biomethane potential of the study area.	(Pappalardo *et al*., 2022)
Maize silage, fermentable fungal biomass	Digestate, un-digestate at thermophilic and mesopholic temp.	Fungal cultures on maize silage and dig estate leads to increased methane production with negative emission.	(Götze *et al*., 2022)
Mixed fruit and vegetable (MFV) biomass	Tween 80 surfactant-assisted ultrasonic fragmentation, soluble organic matter	Surfactant combined with UF is the most effective method in Mixed fruit and vegetable (MFV) biomass for bio methane production.	(Shanthi *et al*., 2023)
Livestock manure approximate	Survey report evaluated	Approximate 27000 million m^3 of biogas could be generated and use heat energy and electricity due to cover shortage of bio fuel and heavy burden less on the imported and costly fuel.	(Muhammad *et al*., 2021)
Organic material, domestic waste water	Loading rate, submerged anaerobic membrane bioreactor (SAnMBR)and ceramic filter	Co-digestion-based SAnMBR is sustainable and efficient waste management method.	(Rajneesh *et al*., 2022)
Kitchen dump	Design different technological aspects and analysis kitchen waste	A logical and basic use of kitchen waste could be easier by planning suitable management strategies	(Esteban-Lustres *et al*., 2022)
Corn stover. urea	Anaerobic conversion efficiency by hydrothermal depolymerization technique	To increase 20-23% methane for growing economic efficiency.	(Yao *et al*., 2022).
General biomass	Up-gradation technology likewise Asia and EU countries for biomethane	Between renewable energy and conventional energy to ensure green environment and energy security, reducing public health hazards and promoting rural build up.	(Shengrong *et al*., 2022).

techniques, smart policy frameworks and inter-disciplinary research collaborations is set to transform biomethane production from waste maize flour, deoiled cake, cow dung and fruit pits into a key component of the global renewable energy transition.

Conclusion

The present study focuses on identifying biomass substrates with high calorific values, an area that has not been extensively explored in the existing literature concerning biomethane production. The research findings reveal that neem deoiled cake (NDC) possesses the highest calorific value among the tested substrates, measured at 5219 Kcal/Kg, surpassing that of mango kernel (MK) (4932 Kcal/Kg), waste maize flour (WMF) (4187 Kcal/Kg) and cow dung (CD) (1820 Kcal/Kg). Furthermore, it was concluded that NDC demonstrates a significantly higher heating value compared to other deoiled cakes, such as Jatropha, reported in previous studies with heating values typically ranging between 4500-4800 Kcal/kg. Similarly, WMF exhibited a higher calorific value than wheat flour, which is generally reported to have a heating value of approximately 3600-3800 Kcal/Kg in the literature. These comparative analyses emphasize that the selection of high-calorific biomass materials has a substantial positive impact on enhancing biomethane production. The study conclusively highlights that biomass with superior heating values, such as NDC and WMF, can significantly improve the efficiency and scalability of biomethane generation systems.

Conflict of Interest. The authors declare that they have no conflict of interest.

References

Bianco, F., Senol, H., Papirio, S.T., Zenk, H.I., Kara, A.Y., Ataso, S.E. 2022. Combined ultrasonic-hydrothermal pretreatment to improve the biomethane potential of hazelnut shell. *Biomass and Bioenergy*, **165:** 106554.

Dębowski, M., Kisielewska, M., Kazimierowicz, J., Rudnicka, A., Dudek, M., Romanowska-Duda, Z., Zieliński, M. 2020. The effects of microalgae biomass co-substrate on biogas production from the common agricultural biogas plants feedstock. *Energies*, **13:** 2186.

Deheri, C., Acharya, S.K. 2022. Purified biohythane (biohydrogen+biomethane) production from food waste using CaO_2+$CaCO_3$ and NaOH as additives. *International Journal of Hydrogen Energy*, **47:** 2862-2873.

Djalma, N.F.J.A., Machado, P.G., Vega, F.J., Coelho, S.T., Woods, J. 2022. Liquefied biomethane from sugarcane vinasse and municipal solid waste: sustainable fuel for a green-gas heavy duty road freight transport corridor in Sao Paulo state. *Journal of Cleaner Production*, **335:** 130281.

Dragusanu, V., Lunguleasa, A., Spirchez, C. 2022. Evaluation of the physical, mechanical and calorific properties of briquettes with or without a hollow made of wheat (*Triticum aestivum* L.) straw waste. *Applied Sciences*, **12:** 11936.

Esteban-Lustres, R., Torres, M.D., Piñeiro, B., Enjamio, C., Domínguez, H. 2022. Intensification and biorefinery approaches for the valorization of kitchen wastes-a review. *Bioresource Technology*, **360:** 127652.

Glivin, G., Mariappan, V., Premalatha, M., Krishnan, H.H., Sekhar, S.J. 2022. Comparative study of biogas production with cow dung and kitchen waste in fiber-reinforced plastic (FRP) biodigesters. *Materials Today: Proceedings*, **52:** 2264-2267.

Götze, H., Austen, D., Drescher-Hartung, S., Wilharm, E. 2022. Enhanced biomethane production from fibre-rich digestate by in-process produced fungal biomass and enzymes. *Bioresource Technology Reports*, **18:** 101-105.

Gunda, M., Annie, M. 2023. Value addition through biohydrogen production and integrated processes from hydrothermal pretreatment of lignocellulosic biomass. *Bioresource Technology*, **369:** 128386.

Shanthi, M., Sundaramahalingam, M.A., Rajeshbanu, J., Sivashanmugam, P. 2023. Surfactant-assisted ultrasonic fragmentation of mixed fruit and vegetable biomass: its impact on biomethane yield and energy analysis. *Fuel*, **334:** 126617.

Khan, M.U., Ahmad, M., Sultan, M., Sohoo, I., Ghimire, P.C., Zahid, A., Sarwar, A., Farooq, M., Sajjad, U., Abdeshahian, P., Yousaf, M. 2021. Biogas production potential from livestock manure in Pakistan. *Sustainability*, **13:** 6751.

Olatunji, K.O., Madyira, D.M., Ahmed, N.A., Adeleke, O., Ogunkunle, O. 2023. Modeling the biogas and methane yield from anaerobic digestion of *Arachis hypogea* shells with combined pretreatment techniques using machine learning approaches. *Waste and Biomass Valorization*, **14:** 1123-1141.

Pappalardo, G., Selvaggi, R., Pecorino, B. 2022. Biomethane production potential in southern Italy: an empirical approach. *Renewable and Sustainable Energy Reviews*, **158:** 112190.

Papurello, D., Canuto, D., Santarelli, M. 2022. CFD model for tubular SOFC stack fed directly by biomass. *International Journal of Hydrogen Energy*, **47:** 6860-6872.

Piechota, G. 2021. Removal of siloxanes from biogas upgraded to biomethane by cryogenic temperature condensation system. *Journal of Cleaner Production*, **308:** 127404.

Rajneesh K.G., Robert, V., Haitham, A., Anh, B., Nandkishor, M., Stephen, G., Shobha, M., Dimuth, N. 2022. Recovery of biomethane from a submerged anaerobic membrane bioreactor treating domestic wastewater blended with semi-solid organic wastes discharged from residential establishments. *Environmental Technology and Innovation*, **27:** 102763.

Salehiyoun, A.R., Sharifi, M., Di Maria, F., Zilouei, H., Aghbashlo, M. 2022. Effect of substituting organic fraction of municipal solid waste with fruit and vegetable wastes on anaerobic digestion. *Journal* *of Material Cycles and Waste Management*, **21:** 1321-1331.

Shengrong, X., Siqi, Z., Ying, W., Yanbo, W., Jinghui, S., Xingang, L., Xiaojiao, W., Gaihe, Y. 2022. What can we learn from the experience of European countries in biomethane industry: taking China as an example. *Renewable and Sustainable Energy Reviews*, **157:** 112049.

Siegrist, A., Bowman, G., Burg, V. 2022. Energy generation potentials from agricultural residues: the influence of techno-spatial restrictions on biomethane, electricity and heat production. *Applied Energy*, **327:** 120075.

Souvannasouk, V., Shen, M., Trejo, M., Bhuyar, P. 2021. Biogas production from Napier grass and cattle slurry using a green energy technology. *International Journal of Innovative Research and Scientific Studies*, **4:** 174-180.

Yao, L., Liang, Z., Xiaoyu, Z., Beibei, Y., Xiujin, L., Hairong, Y. 2022. Depolymerization of corn stover by urea-hydrothermal pretreatment for efficient biomethane production and microbial community analysis of anaerobic digestion. *Journal of Cleaner Production*, **380:** 134978.