JOURNAL OF MARITIME RESEARCH

SPECIAL ISSUE (2026) pp 248–254

ISSN: 1697-4840, www.jmr.unican.es

Green Bio-Energy: Kinetic Modeling of Biogas Production by Co-Digested Organic Wastes

Ramaiah Thirumalaikumar[1,*], Jaikumar Vasudevan[2,*], Krishnan Saravanakumar[3]

ARTICLE INFO

Special Issue:
1st International Maritime and Logistics Conference;
February 10-11, 2026.
National University of Science & Technology (NU), Oman

Article history:
Received 15 Feb 2026;
in revised from 24 Feb 2026;
accepted 05 Jun 2026.

Keywords:
Biogas, *Prosopis juliflora*, Organic Waste and Marine Applications.

ABSTRACT

Biogas is one of the leading alternative renewable energy sources produced by the anaerobic digestion of organic waste such as animal waste, agricultural crops and algae biomass. This research work investigates biogas production through the anaerobic mixed digestion of camel waste with Marine macro algae (*Ulva* and *Prosopis juliflora*) for sustainable energy generation for Marine facility applications. The algal biomass with the camel dung was loaded into anaerobic biodigester (20 L), and the mixture was homogenized at 450 rpm using a mechanical stirrer. The yield of the biomass is estimated by first-order kinetic model and the essential parameters for efficient biogas generation by pH 7 and the optimum temperature of 37 °C with the agitation speed of 450 rpm. The work indicated the reduction in total suspended solids (TSS) to below 2000 mg/L and a decrease in turbidity to approximately 500 NTU within the first 12 hours. The first-order kinetic model, with a rate constant of k = 1, yielded the highest volume of biogas when compared to the other investigation. This research contributes to the sustainable energy field by exploring biomass as a renewable energy source for marine applications. It supports cleaner energy use in the maritime sector while reducing environmental impacts and GHG emission and the effective utilization of organic waste.

1. Introduction.

Fuel is an energy-containing element used in several activities, such as the generation of power and the driving of machinery and operational equipment. Fuel contributes 88% of global energy, predominantly from oil, and supports the economies of the leading oil-producing countries. It is essential to have regulations that govern the quality of gasoline because it is a resource utilized by numerous sectors of the global economy. Consequently, various categories of fuel exist, including gasoline, diesel, and fuel oil. Oil exploration also finds employment in a range of contemporary fields, including detergents, polymers, and so on. However, the global perspective regards this fuel as a non-renewable energy source detrimental to both the environment and human health. In recent centuries, gasoline has been recognized as a crucial energy source worldwide, especially in the Indian subcontinent and the Global South. Many researchers claim that fossil fuels may eventually become extinct. Subsequently, the most substantial work focused on modifying fuel-related environmentally friendly alternatives to conventional fuels. These alternatives are essentially environmentally sustainable, which has led researchers to explore various forms of alternate fuels (Appell, 1975; Angelidaki and Ellegaard, 2003; Appels et al., 2011; Ariyanto et al., 2017; Alherbawi et al., 2021; Arifan, Abdullah and Sumardiono, 2021).

Alternative fuel resources play a key role in the energy production sector. There are various methods available to produce

[1]Process Engineering Department, National University of Science and Technology – International Maritime College Oman, Sohar, Sultanate of Oman. E-mail Address: thirumalai@imco.edu.om.

[2]Chemical Engineering Department, Sri Sivasubramaniya Nadar College of Engineering, Chennai, Tamil Nadu, India. E-mail Address: jaikumarv@ssn.edu.in.

[3]College of Engineering and Technology, University of Technology and Applied Sciences, Sohar, Sultanate of Oman. E-mail Address: Saravana.Krishnan@utas.edu.om.

*Corresponding authors: Ramaiah Thirumalaikumar, E-mail Address: thirumalai@imco.edu.om; Jaikumar Vasudevan, E-mail Address: jaikumarv@ssn.edu.in.

renewable energy, such as natural gas, fossil fuels, tidal, wind, and solar panels. Even though it is still potential research for alternative fuels, especially in the production of biogas through the Marine Macro Algae mixed co-digestion method. The previous analysis (Murugesan et al., 2022) studied the production of biogas through the combination of paper waste and cow waste in a 1:1 ratio, using an air-closed bioreactor at temperatures ranging from 26 °C to 43 °C. The previous results showed a gas production of 6.23/07 dm^3/kg, and the blending process increased the cumulative gas yield to 9.40/11 dm^3/kg, indicating a significant increase in gas output. In addition, mixing the paper waste with cow dung causes persistent gas flammability during the waste's digestion phase (Chu and Karr, 2016).

Rumen fluid functions as an inoculum for cattle manure, leading to the production of biogas (Elliott et al., 2012). The addition of rumen fluid boosted the production rate by enhancing the conversion of biogas. Furthermore, the researchers (Kafle and Kim, 2013) analyzed the performance of an anaerobic digester using a combination of apple waste and swine manure. Various trials were conducted, and the initial assessment indicated the rate of gas production from swine manure and apple waste. The second run investigated the effect of waste and manuring mesophilic and thermophilic temperatures in a continuous manner. According to their research, methane levels rose from 146 to 190 mL/g in just 30 days, and the mixture enhanced the rate of biogas production by approximately 16% and 48% at mesophilic and thermophilic conditions, respectively.

In 2013, researchers identified fish waste silages capable of producing methane and biogas at rates of 441–482 mL/g VS and 71–763 mL/g VS, respectively. Further studies on *Laminaria digitata* revealed that optimal treatment conditions, lasting 0 to 10 minutes at temperatures between 35°C and 39°C, enhanced biogas production by 20%. Treated Macroalgae demonstrated significantly higher yields compared to untreated samples, with mathematical modelling providing critical insights into the ideal conditions for maximizing biogas output (Pramanik et al., 2019; Mungoche et al., 2025).

In northern Jordan, biogas has proven to have a positive economic impact by reducing dependence on expensive fossil fuels (Angelidaki and Ellegaard, 2003). Utilizing local raw materials, a system comprising 7 m^3 biogas holder, 15 m^3 manure tank with 22 m^3 subterranean digester achieved biogas yields equivalent to 4 kg of liquefied petroleum gas and methane, with efficiencies of approximately 60% or 56%, depending on operating temperatures of 18 °C–20 °C, over 25 to 30 days (van Hal, Huijgen and López-Contreras, 2014).

Twenty percent of *Prosopis juliflora*-blended biodiesel has been shown to have greater thermal efficiency compared to traditional fuel (Patnaik, Abbasi and Abbasi, 2020). In addition, combining *Juliflora* with isopropanol enhances exhaust gas recirculation by 30%, and further addition of additives increased the heat release rate (HRR) by 30% (Elalami, 2020; Raja and Premjeyakumar, 2021; Eschen et al., 2024). Relating compost to grassland cleared of *Prosopis* has proven effective in accelerating soil recovery and enhancing biodiversity (Garcia Alba et al., 2012). Moreover, integrating *Prosopis* biomass with biowaste converts invasive plants into useful resources, as demonstrated by a previous study (Kafle and Kim, 2013).

A study on vermicomposting with *Prosopis juliflora* leaves showed the potential to reuse this invasive species as a valuable product (Pilicka, Blumberga and Romagnoli, 2011; Zhang et al., 2025). By combining earthworms into the composting process, previous work performed better conversion of the hazardous leaves into nutrient-rich Vermi-mix, giving a sustainable solution to soil fertility disputes. Similarly, the hydrothermal liquefaction performance of *Ulva prolifera* mixed with chicken waste and carbon teranitride catalyst maximize the biofuel production for the remedial for traditional fuel. Findings revealed that the chemical composition of the algae plays a vital role in thermal degradation, giving important insights into optimizing biogas production through anaerobic digestion (Thirumalaikumar and Jaikumar, 2024).

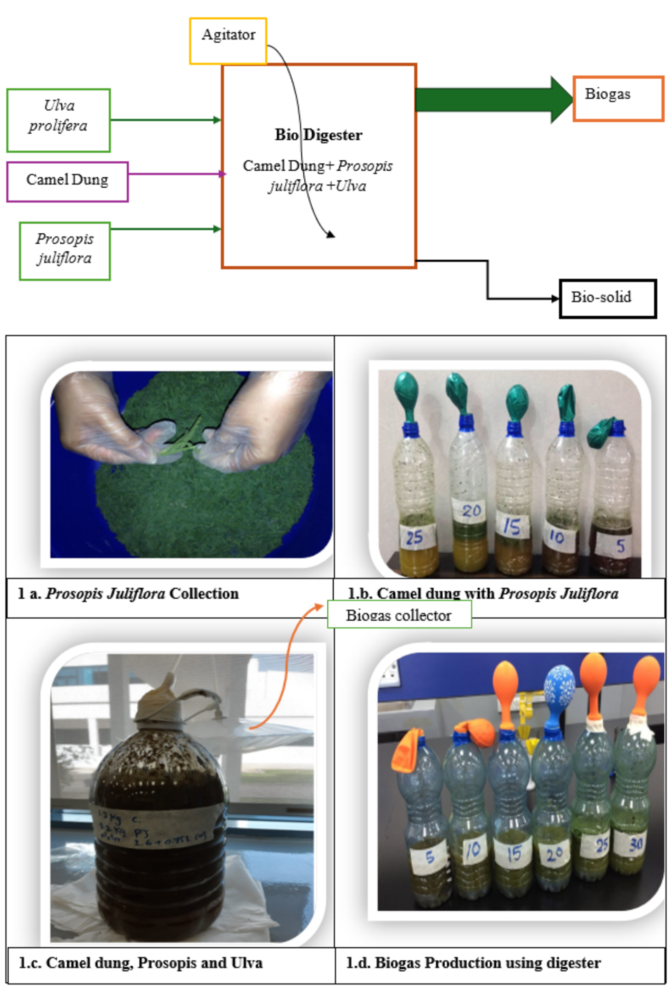
The review has investigated a co-digestion strategy using *Ulva prolifera* and second-generation organic wastes to enhance biogas production. It is clearly revealed that the combination of *Ulva prolifera* with lignocellulosic residues enhances methane yields and optimization parameters for a better yield (Elliott et al., 2012; Garcia Alba et al., 2012; Kafle and Kim, 2013).

The modelling studies evaluate the marine macro algae performance using Hydrothermal liquefaction estimate the expected potential for biogas and other side cuts production (Rani et al., 2012, 2013; Ramaiya and Vasudevan, 2024). The other investigated work emphasizes the significance of optimizing biomass cultivation and harvesting techniques to maximise biogas yield, with *Ulva prolifera* as a sustainable feedstock for biogas generation. Previous literature indicates a lack of kinetic modelling studies examining the co-digestion of Marine algae *Ulva* and *Prosopis juliflora* in combination with camel manure, despite the latter showing greater performance in biogas production. This study investigates the effects of the reaction sequence and rate constants in the anaerobic co-digestion process, using pretreated *Prosopis juliflora*, Marine macroalgae *Ulva*, and Camel dung as co-substrates.

2. Materials and Methodology.

This experimental work involves the collection of fresh camel dung from multiple farms in Kanchipuram, Tamil Nadu, India, and the gathering of *Prosopis Juliflora* leaves from plants located in the northern regions of select rural districts (Kanchipuram and Villupuram) in Tamil Nadu. The Collected *Prosopis Juliflora* leaves are dried for various time intervals (4 hr, 6 hr, 8 hr, 12 hr, 24 hr, 48 hr, 3 days and 1 week). The dried leaves are crushed and create uniform substrates (Fig. 1b). The weighed Marine macroalgae *Ulva Prolifera* (100 gm, 200 gm, 300 gm, 400 gm and 500 gm) were added in various ratios, including 1:0.5, 1:2, 1:3, 1:4, and 1:5 following the grinding of pretreated dried leaves of *P. Juliflora* (Fig. 1c). The biomass substrates, along with camel dung, were loaded into an anaerobic biodigester shown in the schematic Figure 1 (refer Fig. 1a, 1b, 1c, 1d). The loaded slurry was homogenized at 450 rpm using a mechanical agitator and kept at the proper temperature. Additionally, a pH indicator is used to monitor the pH level throughout the process. This experiment evaluates various parameters, including mixing time, total solids, total suspended solids, and reaction duration (ranging from 4 hrs till 7 days) to assess their influence on biogas production. The process involves a series of chemical transformations (Hydrolysis, Acidogenesis, Acetogenesis, and Methanogenesis) that convert fermented biomass into biogas. Biogas is stored in a designated gas container, whereas the residual material resulting from substrate conversion is commonly used as fertiliser for crops. In this work, the proportions of the feedstock components *Prosopis juliflora*, *Ulva prolifera*, and camel dung were modified and the experiment was repeated in accordance with previous methodologies (Appels et al., 2011; Budiyono, Syaichurrozi and Sumardiono, 2013; Baicha et al., 2016). This research work investigates process parameters, such as mixing time, methane yield per kilogram of feedstock, hydraulic retention time (HRT), turbidity, total suspended solids (TSS), total solids (TS), and the performance kinetic model predicting the biogas production efficiency.

Figure 1: Schematic for digester setup.



Source: Authors.

3. Results and Discussion.

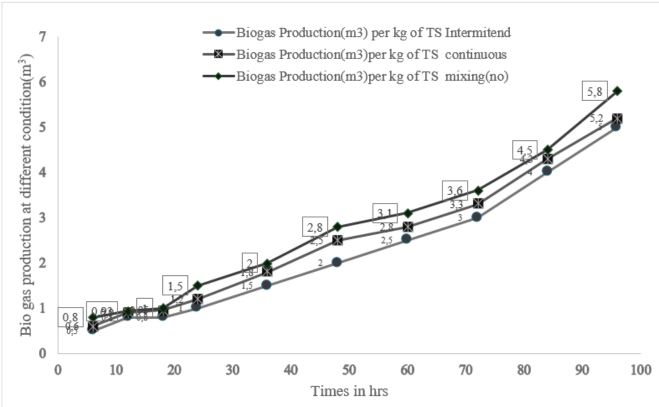
3.1. Mixing Time Effect on Bio-Gas Production.

The experimental work studied the effectiveness of anaerobic digesters operating under different mixing conditions such as continuous, intermittent, and no mixing. The results clearly state that the mixing time impactfully influences the efficiency of biogas production under different operating conditions of the digesters. Continuous mode produced the highest biogas yield, pursued by intermittent mixing, though the absence of mixing yielded the lowest output. This research identified the correlation between mixing time, biogas production, and remaining biosolid amount; the trend clear that the following quantity of *Prosopis Juliflora* (0.2 kg) into the *Ulwa prolifera* and camel dung mixture, with the operating temperature of 37 °C and stirrer speed of 450 rpm for five days. The experimental findings are displayed in Fig. 2, indicating a substantial increase in biogas quantity under no mixing (5.8 m^3 per kg of Total solids) when compared to continuous (5.2 m^3 per kg of TS) and intermittent mixing conditions (4.8 m^3 per kg of TS). The feed mixture consisting of pre-treated *Ulwa* mixed with *Prosopis Juliflora* and Camel dung exhibited a higher conversion rate, resulting in a strong methanogenesis reaction and consistent upward trends. This is due to the interactive effects among the feed components, which together provide a balanced nutrient profile that supports extraordinary microbial activity and is responsible for enhanced biogas production. In addition, Figure 2a, the consistent temperature and agitation conditions facilitated the breakdown of complex organic matter, thereby improving overall anaerobic digestion efficiency. The higher biogas generation is due to the synergistic effects of the feed components. The overall result, increased biogas yields also improved the efficiency of the anaerobic digestion process. Several previous studies have confirmed current findings (Garcia Alba et al., 2012; Kafle and Kim, 2013).

3.2. Effect of Total Suspended Solids Impact on Bio-Gas Production.

The efficiency of Total Suspended Solids (TSS) removal performances in optimizing biogas production. The organic matter in the feedstock is a key parameter for the microbial activity and the efficiency of TSS conversion impact on biogas yield. Figure 3 shows the performance of the biodigester in TSS efficiency. The percentage of TSS efficiency slowly substantially growing from 78% to 90% within 24 hours. In addition, the TSS removal efficiency depends on the anaerobic digestion process and the physicochemical reactions in the effluent. The time intervals increased to 30, 36, 42, and 48 hours. This study proves relatively better performance compared to previous research (I Nyoman and Seno, 2010; Ariyanto et al., 2017). Effective TSS conversion reduces the volume of solid waste, thereby lowering disposal costs and enhancing the marine environment.

Figure 2: Time (vs) Production of biogas at different conditions.



Methane production rate per kg vs mixing time.

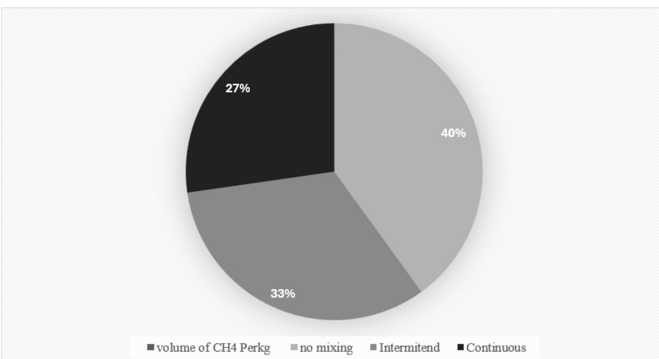


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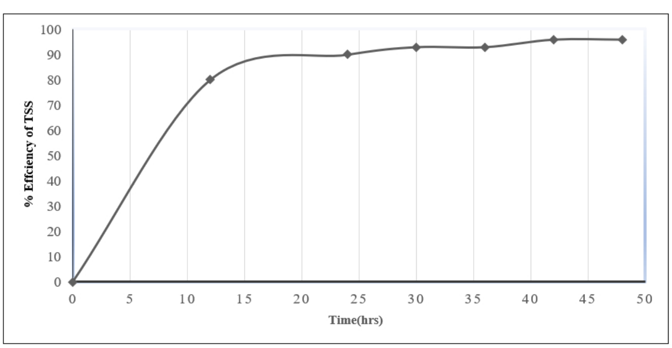
Figure 3: Total suspended solid efficiency with time.



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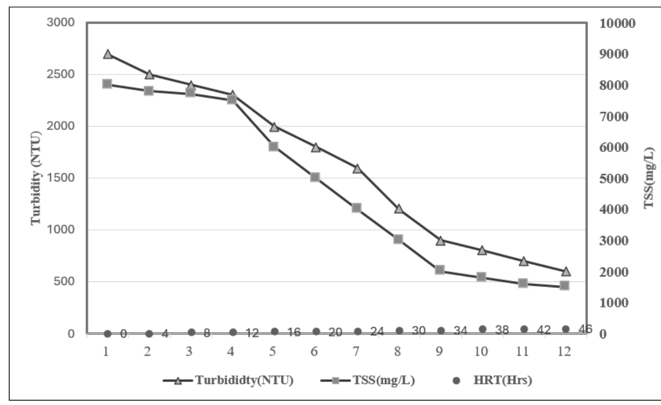
3.3. Impact of Hydraulic Retention Time on Total Suspended Solids and Turbidity.

Figure 4 discusses the relationship between Total Suspended Solids (TSS), turbidity, and Hydraulic Retention Time (HRT) in a treatment process, indicating the impact of continued HRT on reducing solid content and improving water clarity. Initially, TSS and turbidity levels are high, exceeding 8000 mg/L and 2500 NTU, respectively. As HRT rises, a meaningful decline is observed, especially 6 hours later, TSS falling below 2000 mg/L and turbidity nearing 500 NTU by 12 hours. This trend highlights HRT in encouraging the degradation and settling of suspended particles. Additional retention times improves the conversion of solids into smaller, extremely digestible molecules, which is essential for anaerobic digestion processes (Kafle and Kim, 2013; Ramaiya and Vasudevan, 2024). When compared to short HRT, which reveal poor breakdown and greater turbidity levels, systems with optimized HRT (8–12 hours) establish higher efficiency in reducing both TSS and turbidity, the output in improved performance and greater biogas yields (Arifan, Abdullah and Sumardiono, 2021).

Figure 4: Impact of hydraulic retention time on total suspended solids and turbidity.



Source: Authors.

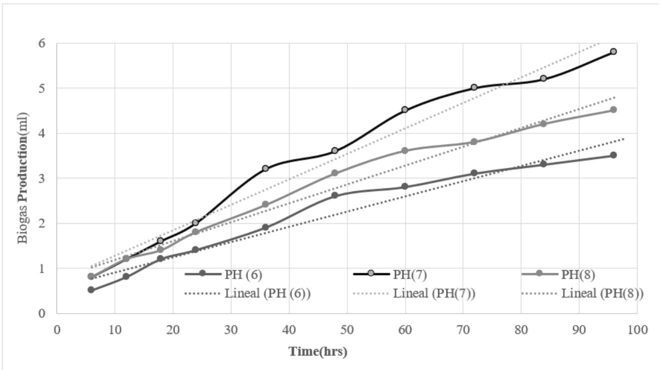
3.4. Effects of pH Changes on Biogas Production.

Figure 5 shows the effect of pH values of 6, 7, and 8 on biogas production for 100 hours, highlighting the suitable pH conditions. This research shows the higher biogas yield was identified at pH 7 for 96 hours, it clearly states that neutral pH enhances microbial activity. When pH 8, biogas production was medium (4.2 mL to 4.5 mL), it confirmed that the alkaline conditions inhibit few microbial activities. In case of pH 6 observed in lower yield (3 mL) due to the reduction of methanogenic archaea under acidic conditions, which is crucial for methane formation. Similar trends have been reported in past studies (Mähnert and Linke, 2009; Appels et al., 2011). Furthermore, earlier research (Arifan, Abdullah and Sumardiono, 2021) has observed that pH extremes reduce the stability of anaerobic processes by hindering both hydrolysis and methanogenesis. These findings confirm that maintaining a neutral pH is essential for maximizing biogas production, consistent with the results obtained in the study (Kafle and Kim, 2012; Lutzu and Dunford, 2019).

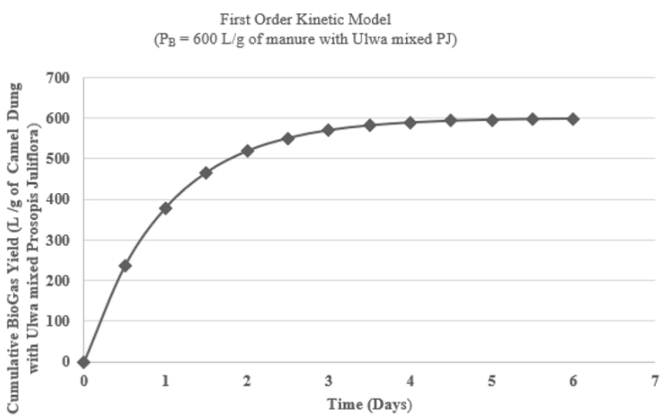
3.5. Kinetic Modelling Investigation of Bio-Gas Yield.

The experimental data were used to evaluate the suitability of the model for kinetic analysis. This research indicates the order of the kinetic model and provides additional information about the hydrolysis rate constant. The model investigation and hydrolysis govern the entire process, with the availability of the substrate serving as the limiting factor. The model (Levenspiel, 1998) is given as follows:

Figure 5: Effect of pH changes on biogas production.



Evaluated Model for Biogas Yield (600L/g of Dung Mixture) Vs. Time (D).



Source: Authors.

$$P = M_B\left[1 - e^{-kt}\right] \tag{1}$$

Here,

P represents the biogas yield (L/g camel manure *Ulwa* mixed *Prosopis Juliflora* added) with respect to time t (days),

M_B is the maximum biogas potential of the substrate (L/g dung added),

k is the hydrolysis rate constant (1/day),

t is the time (day).

As the camel dung mixture (substrate) is assumed to be the limiting reactant, and the reaction follows first-order kinetics, the concentration profile of manure *Ulwa* mixed *Prosopis* shall be obtained using first-order kinetics applied to the concentration of camel manure:

$$\frac{-dC_A}{dt} = kC_A \tag{2}$$

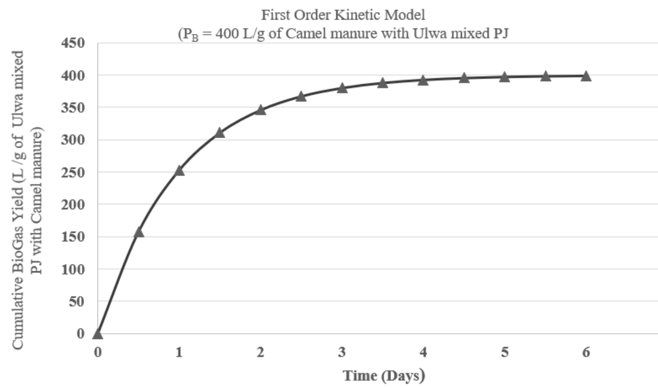
Upon integrating the above equation and applying the integration limits, the equation for concentration of camel manure and *Ulwa* mixed *Prosopis Juliflora* with respect to time shall be obtained as follows:

$$\int_{t=0}^{t} dt = -k\int_{C_A=C_{A0}}^{C_A} dC_A \tag{3}$$

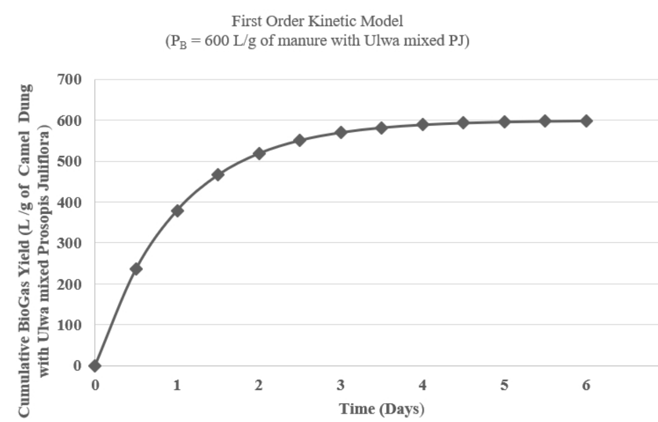
$$C_A = C_{A0}.e^{-kt}$$

Figures 6(a), 6(b), and 6(c) present the total biogas yield in days as a function of time. The following trends illustrate the biogas yield for different quantities, including 400 (g/L), 600 (g/L), and 800 (g/L).

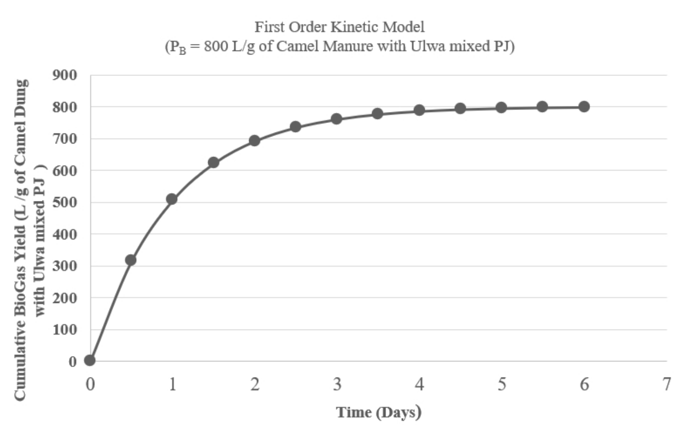
Figure 6: a. Evaluated model for biogas yield (400 L/g of dung mixture) vs. time (D).



b. Evaluated model for biogas yield (600 L/g of dung mixture) vs. time (D).



c. Evaluated model for biogas yield (800 L/g of dung mixture) vs. time (D).

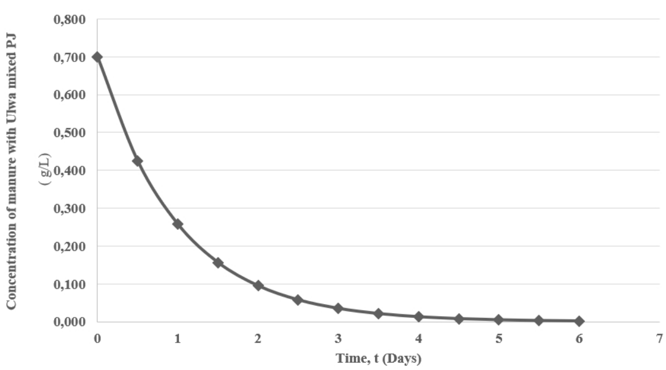


Source: Authors.

The biogas concentration increases at a rate of 0–5 days, with the biomass mixture converting at the fastest rate. On the fifth day, the conversion becomes slower because of the richness of the biosolids. This conversion exhibits a higher degree of agreement with the findings of previous researchers. These experimental data were evaluated using a first-order kinetic model with a rate constant of k = 1, indicating a good fit (Maamri and Amrani, 2014; Zhang, Zhou and Hu, 2021).

Over time, biogas production increases and eventually reaches a peak as the available substrates are consumed. Figure 7 portrays an inverse relationship between dung mixture concentration and time, indicating substrate depletion during anaerobic digestion process. The initial phase of rapid biogas production reflects active hydrolysis and fermentation processes (Arifan, Abdullah and Sumardiono, 2021). As time progresses, biogas production decreases, aligning with first-order kinetic models where the reaction rate is dependent on the concentration of remaining substrate (Appell, 1975). This trend emphasises the importance of optimising substrate quality and adjusting retention time to enhance the efficiency of anaerobic digestion and to maximise biogas production (Osueke et al., 2018; Awais et al., 2020).

Figure 7: Concentration of biomass mixture vs time (D).



Source: Authors.

Conclusions.

This study demonstrates the efficient production of biogas from a feedstock mixture of camel dung, *Ulva* and *Prosopis juliflora* biomass. This biogas can be effectively used for the Marine application as a blended fuel. The optimized parameters pH 7, a temperature of 37 °C, and an agitation speed of 450 rpm, substantially enhanced biogas production. The first-order kinetic model yielded an accurate forecast of biogas generation, with the highest output achieved under these controlled conditions. The decrease in total suspended solids (TSS) and turbidity over time further confirms the effectiveness of the anaerobic digestion process. This research claims that biogas is a sustainable energy alternative, offering significant environmental advantages, including the reduction of organic waste and associated emissions. The findings further prove that biogas production not only contributes to meeting energy demands but also supports improvements in integrated waste management strategies and reduces disposal expenses. Future research could look into the tri-biomass's operational viability analysis for multiple digesters using batch and continuous modes.

Acknowledgement.

The authors gratefully acknowledge the support of National University of Science and Technology (International Maritime College Oman) – Sultanate of Oman for providing research facilities. We also thank the Chemical Engineering Department for their assistance during the study.

Conflicts of Interest.

The authors declare no conflicts of interest.

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