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ANAEROBIC CO-DIGESTION OF DATE PALM WASTE AND COW MANURE FOR ENHANCED BIOGAS PRODUCTION USING BENCH-SCALE CYLINDRICAL DIGESTERS

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ABSTRACT

This study examines the improvement of biogas production through the anaerobic co-digestion of sodium hydroxide-pretreated date palm waste (DPW) and cow manure (CM) under mesophilic conditions. Despite the large availability of date palm residues in arid regions, their high lignocellulosic structure and unbalanced C/N ratio limit their direct anaerobic biodegradability and methane yield. An optimized co-digestion strategy is therefore required to improve conversion efficiency and energy recovery. The primary objective was to identify the optimal mixing ratio that maximizes biogas yield. Experiments were conducted in bench-scale cylindrical digesters operated at 31–35°C over 64 days. Five substrate mixtures were tested, with cow manure to date palm waste ratios of 100:0, 65:35, 45:55, 25:75, and 0:100 of the total solids. Results demonstrated that co-digestion significantly improved biogas production compared to mono-digestion of either substrate. The mixture containing 45% cow manure and 55% date palm waste (A3) yielded the highest cumulative biogas volume of 52.5 L, which was approximately 15.6% greater than the yield from CM alone (45.4 L) and 28.4% greater than DPW alone (40.9 L). This optimal mixture also produced biogas with improved methane content (62%). Statistical analysis confirmed significant differences in biogas production among the mixtures ($p < 0.05$). The findings suggest that co-digestion of pretreated agricultural residues with nutrient-rich animal manure is a technically viable approach for enhancing renewable energy generation and promoting sustainable waste management in arid regions.

KEYWORDS: Anaerobic Digestion, Biogas, Co-Digestion, Date Palm Waste, Mixing Ratio, Waste Valorization.

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1. INTRODUCTION

1.1 Literature Review

Anaerobic digestion (AD) has been widely investigated as a biological conversion process capable of transforming organic wastes into renewable energy in the form of biogas [1–4]. Agricultural residues and livestock manure are among the most studied feedstocks due to their availability and biodegradability [5,6]. However, mono-digestion of lignocellulosic biomass frequently results in limited methane yield because of structural rigidity, high lignin content, and nutrient imbalance [10,11].

Date palm waste (DPW), which is abundantly generated in Saudi Arabia and other arid regions, contains significant cellulose and lignin fractions with a C/N ratio often exceeding 60, far beyond the optimal range of 20–30 required for stable anaerobic digestion [7–10,24]. Several studies have demonstrated that alkaline pretreatment, particularly NaOH treatment, improves biodegradability by partially removing lignin and increasing substrate accessibility [11,28].

Co-digestion has therefore emerged as an effective strategy to improve digestion performance. The combination of nutrient-rich substrates such as cow manure with carbon-rich residues enhances buffering capacity, microbial diversity, and overall methane yield [12–14,18]. Nevertheless, reported optimal mixing ratios vary depending on substrate characteristics and operational conditions. Limited studies have systematically evaluated NaOH-pretreated date palm waste co-digested with cow manure under controlled mesophilic conditions within the Saudi Arabian context.

Therefore, a structured experimental investigation is required to determine the mixing configuration that maximizes biogas production while maintaining process stability.

Global energy demands, coupled with concerns over climate change and fossil fuel depletion, have intensified the search for sustainable energy alternatives [1, 2]. Biogas produced via anaerobic digestion (AD) represents a promising renewable energy source that simultaneously addresses organic waste management challenges [3, 4]. This process not only generates energy but also yields a nutrient-rich digestate suitable for agricultural use [5, 6].

In arid regions like Saudi Arabia, extensive date palm cultivation generates substantial lignocellulosic waste, including fronds and leaves [7, 8]. Disposal often involves open burning, leading to environmental pollution and resource wastage [9]. The recalcitrant structure and low biodegradability of date palm waste (DPW) hinder efficient anaerobic digestion [10]. Pretreatment methods and co-digestion strategies have been developed to overcome these limitations [11, 12]. Co-digestion with nutrient-rich substrates like animal manure can improve nutrient balance, enhance buffering capacity, and increase process stability and biogas yield [13, 14].

This research investigates the anaerobic co-digestion of NaOH-pretreated date palm waste with cow manure. The specific objectives are to (1) determine the optimal mixing ratio for maximizing biogas production, (2) analyze the influence of key process parameters, (3) compare co-digestion performance with mono-digestion, and (4) assess the potential for renewable energy generation from Saudi Arabian date palm residues.

2. MATERIALS AND METHODS

2.1. Substrate Collection and Preparation.

The wastes of date palm (fronds and leaves) were gathered in agricultural farms within Ash Shihyah City in Qassim Region, Saudi Arabia (26.3°N, 43.8°E). The waste substances were then washed using the tap water to remove the soil and impurities, which were then dried under air over a period of 72 hours. The dried material was then shredded mechanically to achieve a particle size of between 2 and 5 cm in size, using a commercial shredder.

The chemical pretreatment involved 5 days of soaking the shredded palm waste in 1 per cent sodium hydroxide (NaOH) solution at ambient temperature (25℃). The solid to liquid ratio was kept at 1:10. After pretreatment the substrate was rinsed using distilled water until it attained a neutral pH after which it was then drained after 24 hours.

The manure used was fresh cow manure that was received at a dairy farm in the same region. The manure was mixed with the help of a mechanical mixer and it was passed through a 2-mm mesh to eliminate the rough or indigestible contents. The analysis of the two substrates was done using standard procedures [20], and the outcome shown in Table 1.

Substrate characteristics are summarized in Table 1.

2.2. Experimental design and reactor set up.

A single series of experiments (Series A) was conducted using five identical bench-scale cylindrical digesters (A1 to A5). Each digester was constructed from high-density polyethylene with a height of 40 cm, a diameter of 12 cm, providing a total

volume of approximately 4.5 L, and a working liquid volume of 3.2 L. Each unit was equipped with two orifices: one gas outlet connected to a 10.2 L biogas collection cylinder, and another for sampling and manual mixing. A manual mixing rod was used for daily agitation. The reactors were immersed in a temperature-controlled water bath.

The five tested substrate mixtures varied in the proportion of cow manure (CM) to date palm waste (DPW) as a percentage of total solids:

A1: ⟶ (100:0DPW:CM),
A2: ⟶ (25:75CM:DPW),
A3: ⟶ (45:55CM:DPW),
A4: ⟶ (65:35CM:DPW),
A5: ⟶ (100:0 CM:DPW).

The schematic configuration of the experimental setup is illustrated in Figure 1.



Figure I. A Diagrammatical Illustration Of A Bench-Scale Anaerobic Digester That Involves The Depiction Of The Following Parameters (Height = 40cm, Diameter = 12cm), Gas Outlet, Sampling Port And The Working Volume Of 3.2L.

2.3. Operational Parameters

The anaerobic digestion experiment was carried out under mesophilic conditions and the temperature was maintained at 31–35℃ in the period of 64 days of hydraulic retention. The digital temperature monitoring system is presented in Figure 2.

The preliminary pH values were adjusted to 7.0 using 1% HCl or NaOH. Manual mixing was performed twice a day in order to reduce stratification and increase the contact between substrate and micro-organisms. The pH stabilization profile during digestion is shown in Figure 3.

Process monitoring included daily measurement of temperature, pH, biogas production measured by water displacement method, and methane composition.

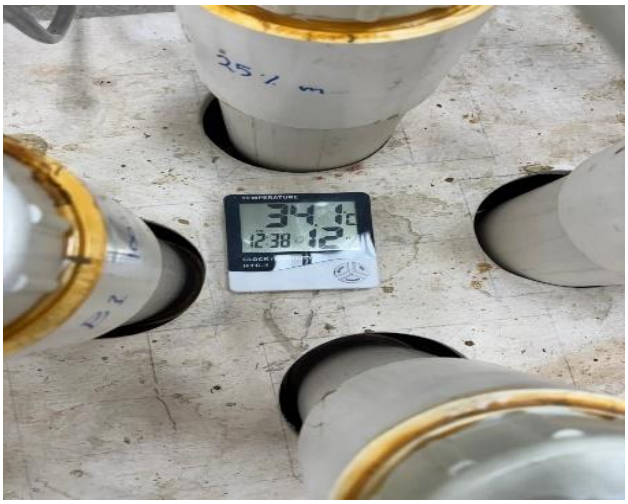


Figure II. Digital Temperature Monitoring System That Shows How The 31-35℃ Temperature Range Was Maintained Throughout The Experiment.



Figure III. Ph Profile Of The Digestion Process, Which Demonstrates The Ability To Maintain An Optimal Ph Range Of Methanogenic Activity.

2.4. Analytical Methods

Biogas Measurement: The water displacement method was used in measuring daily biogas production [21]. A calibrated 10.2 L gas collection cylinder was used, where the volume of water displaced was directly proportional to the volume of biogas collected. Daily measurements were recorded for 64 days.

Methane Content: Methane percentage in the biogas was determined weekly using a gas chromatography system that had a thermal conductivity detector. The results were confirmed by ignition tests. Visual confirmation of methane combustion is presented in Figure 4.

Chemical Analysis: Total solids (TS), volatile solids (VS), chemical oxygen demand (COD) and alkalinity were determined according to Standard Methods [20].



Figure IV Visible Flames Produced During Combustion, Demonstrating Successful Ignition And Sustained Burning Of The Generated Gas.

Chemical Analysis: Total solids (TS), volatile solids (VS), chemical oxygen demand (COD) and alkalinity were determined according to Standard Methods [20]. Elemental analysis was used to compute carbon-to- nitrogen (C/N) ratios.

2.5. Statistical Analysis

All experiments were repeated and the results are given in form of mean values with standard deviation. One-way analysis of variance (ANOVA) was conducted by SPSS software (Version 28.0) to determine the important variation in the mean of treatment. The HSD test was used to statistically compare post-hoc tests at a significance level of $p < 0.05$. Pearson correlation coefficient was used to determine correlation between the parameters in the process and the yield of biogas.

2.6. Mathematical Model

The daily biogas production ($V_{biogas,i}$) was measured using the water displacement method with a calibrated 10.2 L collection cylinder. The daily biogas production rate was calculated as:

$$R_i = V_i - V_{i-1} \quad (1)$$

The cumulative biogas yield over the 64-day period was calculated as:

$$V_{cum} = \sum_{i=1}^{n} V_i \quad (2)$$

The specific biogas yield per unit volatile solids added was determined as:

$$Y_{VS} = \frac{V_{cum}}{m_{VS}} \quad (3)$$

The Modified Gompertz model describing cumulative biogas production is given by:

$$B(t) = P \exp\left[-\exp\left(\frac{R_m e}{P}(\lambda - t) + 1\right)\right] \quad (4)$$

3. RESULTS

3.1. Substrate Characteristics

Table 1 gives the physicochemical characteristics of the raw materials. The waste of date palm had high volatile solids (85.2) and carbon content (45.3) and the content of nitrogen was low (0.68). Cow manure had more balanced characteristics, as C/N ratio was 24.3, alkalinity was increased (5750mg/L as $CaCO_3$) and microbial population was also high.

Substrate characteristics are summarized in Table 1.

Table I. Characteristics Of Raw Substrates (Mean ± SD, N=3).

Parameter	Data Palm Waste	Cow Manure	Units
Volatile Solids (VS)	85.2	76.8	%
pH	6.2	7.1	% of TS
Total Carbon	45.3	41.2	-
Total Nitrogen	0.68	1.70	%
C/N Ratio	66.6	24.3	%
Alkalinity	1250	5750	-
Cellulose	42.5	32.1	mg/L as $CaCO_3$
Hemicellulose	28.3	25.6	%
Lignin	20.1	15.3	%

3.2. Biogas Production from Different Mixing Ratios

The mixing ratio was found to have a positive influence on cumulative biogas production ($p<0.01$). Monogastric digestion of date palm waste (A1: 100% DPW) gave the lowest biogas yield (40.9L), while the 45:55 (cow manure: date palm waste) (A5: 100% CM) mixture gave a comparable production of 45.4L. Mixed manure of intermediate concentrations of 45-65%(A3) cow manure to date palm waste showed important improvement in performance compared to the two extremes. This was the height recorded (52.5 L). This represents a 28.4% increase compared to DPW mono-digestion and a 15.6% increase compared to CM mono-digestion. Performance results are presented in Table 2.

Table II. Experimental Design And Performance Results For Series A (Mean ± SD)

Reactor	CM:DPW Ratio	CM (%)	DPW (%)	Cumulative Biogas (L)	Peak Production Day
A1	0:100	0	100	40.9	56
A2	25:75	25	75	46.7	56
A3	45:55	45	55	52.5	52
A4	65:35	65	35	49.1	48
A5	100:0	100	0	45.4	36

To further examine the progression of biogas generation over time, the daily cumulative production values for all substrate mixtures were recorded throughout the 64-day digestion period. Monitoring the cumulative increase allows evaluation of the startup phase, peak production period, and stabilization stage for each mixture. The detailed cumulative biogas volumes measured at specific time intervals are presented in Table 3.

Table III. Daily Cumulative Biogas Production (L) From Five Substrate Mixtures Over 64 Days Of Anaerobic Digestion.

Day	A1 (100% DPW)	A2(25:75)CM:DPW	A3(45:55)CM:DPW	A4 (65:35) CM:DPW	A5 (100%CM)
1	0	0	0.3	0.5	1.5
2	0.2	0.8	1.5	2.1	6.6
3	0.5	1.5	3.2	5.5	12.4
5	1.1	2.8	6.4	9.8	18.6
7	2.3	4.6	10.1	14.2	24.1
9	3.8	7.2	14.5	18.7	28.5
11	5.9	10.5	19.4	22.9	32.2
13	8.4	14.1	24.8	26.5	35.8
17	11.2	18.3	29.5	30.1	38.4
20	14.5	22.9	34.2	33.4	40.2
24	18.6	27.4	38.6	36.8	42
28	22.4	31.5	42.1	39.5	44
32	26.8	35.2	45.4	41.8	45
36	31.2	38.7	48.2	44.2	**45.4**
40	35.4	42.1	50.1	46.5	40.2
44	38.2	44.5	51.5	48.1	34.3
48	39.7	45.8	52.1	**49.1**	27.5
52	40.5	46.4	**52.5**	46.2	20.5
56	**40.9**	**46.7**	50.5	42.4	13.5
60	40.3	45.7	47.6	37	7
64	39.5	43.5	43	31	1.5

Cumulative biogas production trends for all mixtures are illustrated in Figure 5.

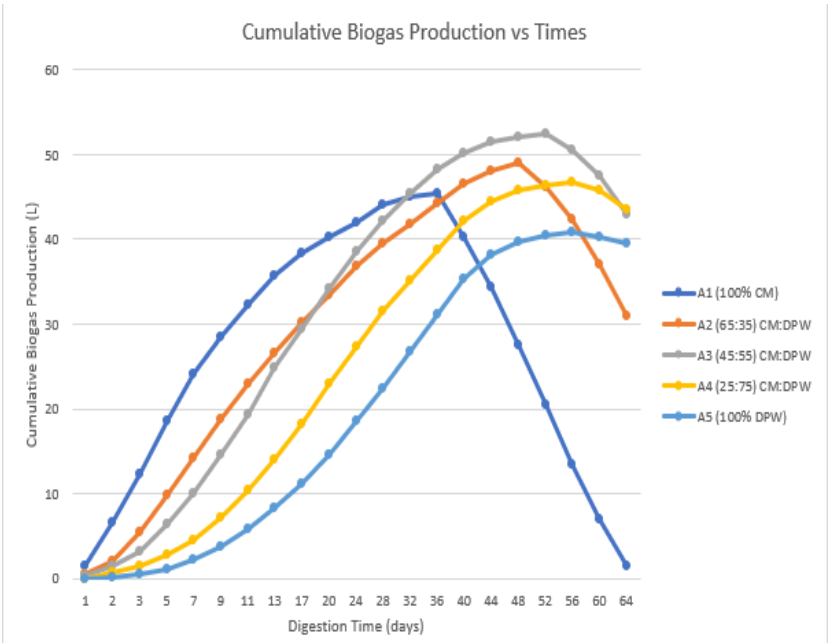


Figure V. Cumulative Biogas Production From Different Substrate Mixtures Over 64 Days Of Digestion.

3.3. Monitoring Process parameters.

Temperature and pH: The temperatures in the digestion system were constantly maintained as 31 - 35℃ The pH values were initially different depending on the composition of the substrate but stabilized within the range of 6.8 to 7.2 at the end of the first week and the best mixtures were composed of 45-65% cow manure that provided a more consistent pH value (7.09). Process monitoring data are summarized in Table 4.

Table IV. Process Parameters During Anaerobic Digestion (Mean Values).

Parameter	Week 1	Week 4	Week 8	Week 9
Temperature (°C)	32.5	32.1	31.8	31.9
pH (Mix A3)	6.9	7.1	7.2	7.1
Daily Biogas (L/day)	1.2	3.8	2.1	0.8
Methane (%)	45.2	58.3	57.6	52.1

3.4. Methane Content and Energy Potentials

The methane concentration in the biogas improved with co-digestion, reaching optimal levels in the 45:55 CM:DPW mixture (62% methane). Mono-digestion of cow manure produced biogas with 58% methane content, while date palm waste alone yielded biogas with 59% methane. The specific biogas yield per unit of volatile solids added (Y_VS) was calculated as 310 L/kg VS for the optimal mixture (A3), which aligns with realistic yields reported for co-digestion systems under mesophilic conditions. Methane and energy results are shown in Table 5.

Table V. Methane Content And Energy Potential Of Biogas From Different Substrate Mixtures.

Substrate Mixture	Cumulative Biogas (L)	Methane Content (%)	Methane Volume (L)	Estimated Energy (MJ)
A1 (100% DPW)	40.9	59	24.1	0.87
A2 (25:75 CM:DPW)	46.7	61	28.5	1.03
A3 (45:55 CM:DPW)	52.5	62	32.6	1.17
A4 (65:35 CM:DPW)	49.1	60	29.5	1.06
A5 (100% CM)	45.4	58	26.3	0.95

Energy calculated assuming methane calorific value of 36 MJ/m³ (50.1 MJ/kg) and biogas density of 1.15 kg/m³. Methane content evolution in biogas from different substrate mixtures are represented in Figure 6.

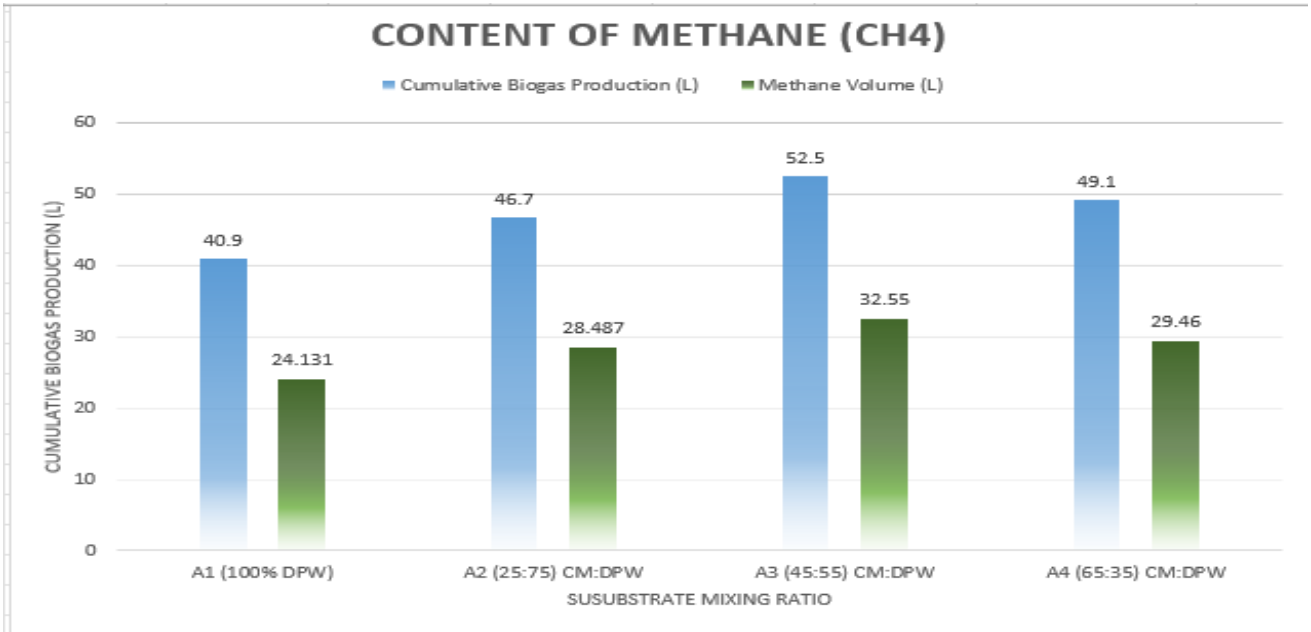


Figure VI. Methane content evolution in biogas from different substrate mixtures during 64-day anaerobic digestion.

The 45:55 CM:DPW mixture (A3) achieved the highest methane percentage (62%), demonstrating that optimal co-digestion enhances both biogas quantity and quality.

3.5. Kinetic Modeling of Biogas Production

The Modified Gompertz model was applied to describe the cumulative biogas production from different substrate mixtures:

$$B(t) = B_0 \cdot \exp\left\{-\exp\left[\frac{R_m \cdot e}{B_0}(\lambda - t) + 1\right]\right\} \quad (5)$$

Where:

- $B(t)$ = cumulative biogas production at time t (L)
- B_0 = maximum biogas production potential (L)
- R_m = maximum biogas production rate (L/day)
- λ = lag phase time (days)
- e = Euler's number (2.71828)

Gompertz kinetic parameters are presented in Table 6.

Table VI. Gompertz Model Parameters For Different Substrate Mixtures.

Mixture	B_0 (L)	R_m (L/day)	λ (days)	R^2
A1	41.2	1.85	3.2	0.997
A2	47.1	2.12	2.8	0.998
A3	53.0	2.45	2.5	0.999
A4	49.5	2.31	2.6	0.998
A5	45.8	1.98	1.5	0.997

The high R^2 values (>0.997) indicate excellent fit of the model to the experimental data. The optimal mixture (A3) exhibited the shortest lag phase (2.5 days) and highest maximum production rate (2.45 L/day).

3.6. Statistical Analysis

One-way ANOVA revealed significant differences in cumulative biogas production between substrate mixtures ($F = 48.72$, $p < 0.001$). Post-hoc analysis using Tukey's HSD test indicated that:

- Mixture A3 (45:55 CM:DPW) produced significantly more biogas than all other mixtures ($p < 0.05$)
- Mixtures A2 and A4 were not statistically different from each other ($p = 0.087$)
- Both A2 and A4 produced significantly more biogas than mono-digestion substrates A1 and A5 ($p < 0.05$)
- No significant difference was found between A1 (100% DPW) and A5 (100% CM) ($p = 0.215$)

Pearson correlation analysis showed strong positive correlation between cow manure percentage and biogas yield up to 45% CM ($r = 0.89$, $p < 0.01$), beyond which the correlation became negative ($r = -0.76$, $p < 0.05$).

4. DISCUSSION

4.1. Co-Digestion to improve Biogas Production

The significant increase in biogas production through co-digestion (up to 28.4% compared to mono-digestion of DPW) supports findings from similar studies on agricultural waste co-digestion [22, 23]. The optimal performance at 45% cow manure inclusion can be explained by several factors:

Nutrient Balance: The Date palm waste had an unbalanced C/N ratio of 66.6, which is more than the ideal of 20-30 of anaerobic digestion [24]. The cow manure had a C/N ratio of 24.3 which was able to rectify this imbalance in co-digestion mixtures, hence making the manure a vital source of nitrogen to nurture the microbes and their functions.

Buffering Capacity: Cow manure (5750 mg L as $CaCO_3$) had a better buffering capacity than palm waste (1250mg L). This buffering capacity maintained the PH level especially at acidogenic phases and countered the PH falls that would otherwise suppress the methanogenic activity.

Microbial Synergy: Cow manure was an efficient inoculum and it provided a rich and varied population of microorganisms, such as hydrolytic, acidogenic and methanogenic microorganisms. This complementation was probably effective in degrading complex lignocellulosic structures that were found in palm waste.

4.2. Comparison to Existing Literature

The current results contradict the results provided by Ofomatah and Okoye [19], who reported mutual inhibition in a bagasse cattle manure co-digestion system. Such inconsistency can be caused by differences in substrate properties, the pre-treatment procedures, or the working conditions. Even though the waste of date palm is lignocellulosic, its compositional characteristics such as the lignin content and structure can vary importantly compared to bagasse.

Conversely, the findings are more consistent with the findings of Phillip et al. [18] that reported the best biogas generation at a ratio of 4:1 of cow manure to fruit waste. Both studies emphasize the importance of equal mixing ratios; however, the exact optimum ratios vary, and this is a substrate-dependent characteristic.

Comparing the current research to the study on kitchen waste by Aljumah and Alyahya [21], it is clear that the current research has lower absolute biogas yields, but the same percentage improvement through co-digestion. This is probably explained by the more stubborn nature of date palm waste as compared to the easy biodegradable kitchen waste.

4.3. Optimization of Process parameters

The mesophilic digestion temperature of 31-35℃ was the best temperature regime, which is similar to the literature of 30-38 ℃ at the mesophilic temperature range [26]. Initial tests that were performed at higher temperatures (45-50℃) had faster startup, but were more unstable and thus supported the choice of mesophilic conditions to be used in long-term operation.

The stable pH of 7.09 in the optimum mixtures means that there is proper buffering and equal activity of the microbes; the range of 6.8-7.4 is the optimum pH ranges of 6.8-7.4 of methanogenesis is established [27] hence explaining the high methane levels in the optimum mixtures.

The retention time of 64 days was used to achieve close to complete digestion, although most biogas production was made during the first 45 days. Such

a time relationship indicates that additional optimization of the retention time is possible depending on the properties of the substrates and the mixing ratios.

4.4. NaOH Pretreatment Effectiveness

The pretreatment with 1 % NaOH during five days was used to improve biodegradability by partially delignifying and swelling the cellulose [28]. Though not measured in this study, similar pretreatment conditions have been found to enhance biogas production of lignocellulosic materials by 30-50% [29]. The following washing process was vital to counter the sodium inhibition, which would otherwise have a negative impact on the activity of microbes [30].

4.5. Scaling Considerations and implication on practice.

The shown biogas yields, which are up to 310 L/kg VS suggest that date palm wastes hold a high potential of energy in Saudi Arabia. Based on the experimental yield of 52.5 L from 2 kg total solids (approximately 1.6 kg VS) in a 4.5 L digester, the specific yield is 32.8 L/kg VS. For estimated annual date palm waste production of 2 million tons in Saudi Arabia [31], with 85% VS content, the theoretical biogas potential is approximately 55.8 million m^3/year, equivalent to 1.12 million GJ of energy.

4.6. Limitations and Future Work

The given study has a number of limitations that should be studied in the future:
Long stability: The 64 day experiment is an initial optimization but long operation is needed to determine process stability.
Continuous operation Batch experiments are not the same as continuous systems used in practice.
Economic analysis: Implementation decisions require a detailed techno-economic analysis.
Digestate quality: No nutrient and agricultural value of digestate was studied.
Alternative pretreatments: Comparison to other pretreatment methods would be able to find more effective options.
These aspects should be covered in future research that investigates:
Fusion with other garbage streams to generate better synergies.
Formulation of local implementation plans.
Maximization of energy balance taking into account pretreatment requirements.
Environmental impacts life cycle assessment.

5. CONCLUSIONS

The current research paper has proven that anaerobic co-digestion of NaOH-pre-treated date palm waste with cow manure is technically feasible in increasing the biogas production.

Key findings include:
1. **Optimal Mixing Ratio:** The 45:55 cow manure to date palm waste mixture (A3) yielded the highest cumulative biogas production (52.5 L), representing a 28.4% improvement over DPW mono-digestion and 15.6% improvement over CM mono-digestion.
2. **Process Efficiency:** The optimal mixture achieved 62% methane content with a total methane yield of 32.6 L, corresponding to an energy potential of 1.17 MJ.
3. **Kinetic Parameters:** Gompertz modeling revealed the optimal mixture had the shortest lag phase (2.5 days) and highest production rate (2.45 L/day).
4. **Statistical Validation:** ANOVA confirmed significant differences between mixtures ($F = 48.72$, $p < 0.001$), with the 45:55 mixture statistically superior to all others.

The study offers effective recommendations to the application of date palm waste-to-energy systems in Saudi Arabia and other similar areas. This solution can help achieve the principles of the circular economy and sustainable development by transforming agricultural residues into renewable energy and generating useful digestate. The next research needs to be directed on the scaling of the process, in-depth economic evaluation, and maximizing the integration with the current waste management systems.

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NOMENCLATURE

Symbol	Description	Unit
Latin Symbols		
AD	Anaerobic Digestion	-
BR	Base fluid ratio (water: ethylene glycol)	-
C	Carbon content	%
C/N	Carbon-to-Nitrogen ratio	-
CM	Cow Manure	-
COD	Chemical Oxygen Demand	mg/L
DPW	Date Palm Waste	-
EV	Electric Vehicle	-
F	F-statistic value from ANOVA	-
GJ	Gigajoule	$J \times 10^9$
HCl	Hydrochloric Acid	-
HRT	Hydraulic Retention Time	days
kJ	Kilojoule	$J \times 10^3$
L	Liter	L
m^3	Cubic meter	m^3
MJ	Megajoule	$J \times 10^6$
N	Nitrogen content	%
NaOH	Sodium Hydroxide	-
p	Probability value (statistical significance)	-
pH	Potential of Hydrogen	-
r	Pearson correlation coefficient	-
SD	Standard Deviation	-
TS	Total Solids	%
T	Temperature	°C or K
V	Volume	L or m^3
VS	Volatile Solids	% of TS
Y	Yield	L/kg VS or L
Greek Symbols		
φ	Volume fraction of nanoparticles	%
μ	Dynamic viscosity	Pa·s
ρ	Density	kg/m^3
Subscripts and Superscripts		
bf	Base fluid	-
cum	Cumulative	-
i	Index (e.g., day i)	-
nf	Nanofluid	-
np	Nanoparticles	-
p	Particle	-
sf	Suspension fluid	-

B_0 = Maximum biogas potential (L)
R_m = Maximum biogas production rate (L/day)
λ = Lag phase time (days)
R^2 = Coefficient of determination
r = Pearson correlation coefficient