



Sustainable Production of Hexadecanoic Acid from *Gmelina arborea* Leaf Biomass via BaCl₂-Catalysed Thermal Hydrolysis

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Abstract. The valorization of underutilised lignocellulosic biomass into value-added chemicals offers a promising pathway for sustainable production and circular bioeconomy development. This study investigated hexadecanoic acid production from *Gmelina arborea* leaf biomass through BaCl₂-catalysed thermal hydrolytic processing under mild conditions. The effects of BaCl₂ catalyst loading (0.5 and 1.0 wt.%) and reaction temperature (50-80 °C) were evaluated, with duplicate experiments conducted to assess reproducibility. Products were characterised and quantified using gas chromatography–mass spectrometry (GC-MS), while the effects of catalyst loading and temperature were evaluated using two-way analysis of variance (ANOVA). Both factors significantly affected hexadecanoic acid production, with a highly significant catalyst-loading-temperature interaction ($p < 0.0001$). At 0.5 wt.% BaCl₂, specific yield decreased progressively with increasing temperature. In contrast, at 1.0 wt.% BaCl₂, specific yield increased from 507.17 mg/g at 50 °C to a maximum average of 599.48 mg/g at 70 °C before declining to 427.65 mg/g at 80 °C. The optimum condition was therefore 1.0 wt.% BaCl₂ at 70 °C, with the highest individual replicate yielding 604.00 mg/g. Experimental reproducibility was satisfactory, with coefficients of variation ranging from 0.99 to 2.72%. The findings demonstrate the potential of BaCl₂-catalysed thermal hydrolysis for converting underutilised *G. arborea* leaves into a commercially relevant bio-based fatty acid. The process supports SDG 9 through innovative biomass conversion, SDG 12 through waste valorisation and resource efficiency, and SDG 13 through the potential reduction of dependence on non-renewable feedstocks. Further optimisation of process variables is recommended to improve yield, efficiency, and sustainability.

Keywords: *Gmelina Arborea*; Hexadecanoic Acid; BaCl₂ Catalysis; Thermal Hydrolysis; Biomass Valorization

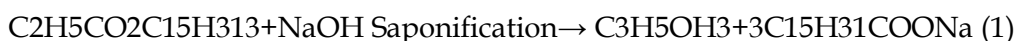
1. Introduction

The global demand for bioactive molecules is increasing because of their diverse applications across pharmaceutical, cosmetic, food and beverage, fragrance, and fuel industries (Jani *et al.*, 2026; Câmara *et al.*, 2024; Abbas *et al.*, 2023). Of particular interest is the potential for producing these valuable molecules from renewable and underutilised resources, including agricultural and plant-based waste biomass such as discarded leaves. The conversion of waste biomass into high-value bioactive molecules provides an attractive pathway for promoting resource efficiency, reducing dependence on fossil-derived feedstocks, and supporting the development of sustainable industrial processes (Akhtar *et al.*, 2025). In addition, the renewable and biodegradable nature of biomass-derived products offers environmental advantages over many conventional petroleum-derived materials, thereby contributing to the transition towards a more sustainable and circular bioeconomy (Rajendran *et al.*, 2025; Akhtar *et al.*, 2025). Agricultural waste, comprising residues generated

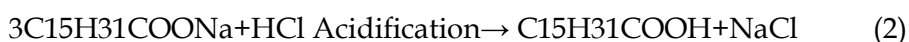
during agricultural production and processing, is an abundant, renewable feedstock that can be converted into value-added chemicals and materials for industrial applications (Yao *et al.*, 2021). The valorisation of these residues offers opportunities to produce materials that can complement or replace petroleum-derived chemicals, thereby reducing the consumption of non-renewable resources and associated environmental impacts (Rajendran *et al.*, 2025; Blasi *et al.*, 2023; Sanchez-Borrego *et al.*, 2021). Such waste-to-value approaches are particularly relevant to the principles of the circular economy, in which wastes are transformed into useful resources rather than being discarded (Munir *et al.*, 2025; Zueva *et al.*, 2024). Consequently, the valorisation of agricultural residues can simultaneously address waste-management challenges, enhance resource efficiency, create economic opportunities, and promote sustainable industrial development (Boudalia *et al.*, 2026; Ufitikirezi *et al.*, 2024).

Among the valuable compounds obtainable from agricultural and plant-based residues is hexadecanoic acid (palmitic acid), a saturated fatty acid with considerable industrial and commercial importance (Vicente-Zurdo *et al.*, 2025; Benito *et al.*, 2025; Adeniyi *et al.*, 2024). Hexadecanoic acid possesses a broad range of physicochemical and biological properties and has been reported to exhibit antioxidant and other bioactive characteristics, in addition to its importance as an industrial chemical (Eisa *et al.*, 2026; Ghfil *et al.*, 2025; Purushothaman *et al.*, 2025). Its versatility has led to applications in cosmetics and personal care formulations, soaps and detergents, pharmaceutical and medical products, and other chemical manufacturing processes (Rani & Bahuleyan, 2024; Kushwaha *et al.*, 2023; Ogbeide *et al.*, 2021). The conversion of agricultural and plant residues into hexadecanoic acid and other high-value bioactive molecules is therefore an important strategy for advancing sustainable bioprocessing and green chemical production (Garg *et al.*, 2026; Kagueyam *et al.*, 2025). Such approaches are consistent with SDG 9 (Industry, Innovation and Infrastructure) through the development of innovative technologies for converting renewable waste resources into value-added products; SDG 12 (Responsible Consumption and Production) by promoting waste valorisation, resource efficiency, and circular production systems; and SDG 13 (Climate Action) by reducing reliance on fossil-based feedstocks and potentially lowering the environmental footprint associated with conventional chemical production (Ibrahim *et al.* 2026a). Furthermore, where biomass-derived molecules contribute to renewable fuel and energy systems, their production can support SDG 7 (Affordable and Clean Energy) (Ibrahim *et al.*, 2026b). Thus, the sustainable production of hexadecanoic acid from waste biomass represents not only a pathway for obtaining an economically valuable chemical but also an opportunity to integrate waste management, renewable resource utilization, industrial innovation, and environmental sustainability within a circular bioeconomy framework.

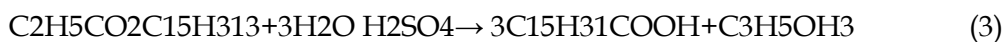
Hexadecanoic acid, commonly known as palmitic acid, is produced conventionally through saponification using sodium hydroxide (Alum, 2024; Mansir *et al.*, 2018). The principal triglyceride is tripalmitin, reacts with sodium hydroxide to produce sodium palmitate (Yoshioka *et al.*, 2023), as illustrated in Equation 1.



The sodium palmitate is acidified with mineral acid to yield hexadecanoic acid, as presented in Equation 2.



Another conventional method of producing hexadecanoic acid is by hydrolysis of palm oil or animal fats and mineral acids like sulfuric acid, followed by fractional distillation of the resulting fatty acid mixtures (Khairuddin *et al.*, 2026; Vilas Bôas & Mendes, 2022). The hydrolysis of palm oil to hexadecanoic acid is catalysed by sulphuric acid (Puangsang *et al.*, 2021; Maulidiyah *et al.*, 2021) and is expressed in Equation 3.



Despite the established industrial production of hexadecanoic acid (palmitic acid) through conventional routes such as saponification of triglyceride-rich oils and hydrolysis of palm oil or animal fats followed by fatty-acid separation, these processes rely predominantly on conventional lipid feedstocks and do not directly address the valorisation of underutilised lignocellulosic biomass. Although agricultural and plant-based residues have increasingly been investigated as renewable sources of value-added chemicals, limited attention has been given to the direct production and recovery of hexadecanoic acid from discarded leaves, particularly *Gmelina arborea* leaf biomass. More importantly, there is a lack of published information on the production yield of hexadecanoic acid from biomass-derived feedstocks under mild catalytic thermal-hydrolytic conditions comparable to those employed in the present study. The influence of barium chloride (BaCl₂) catalyst loading and reaction temperature on hexadecanoic acid formation from *G. arborea* leaves has not been adequately established, and the possible interaction between these operating variables remains insufficiently understood. Consequently, there is a need to determine whether a simple aqueous catalytic process can convert this underutilised leaf biomass into a measurable quantity of hexadecanoic acid while operating at relatively low temperatures and atmospheric pressure.

Furthermore, systematic evaluation of process reproducibility and the statistical significance of catalyst loading–temperature interactions are limited in the available literature. Establishing the optimum combination of catalyst concentration and reaction temperature is therefore necessary for improving product recovery and providing a quantitative basis for subsequent process optimization. The present study addresses these gaps by investigating BaCl₂-catalysed thermal hydrolytic processing of *G. arborea* leaf biomass, evaluating the effects of catalyst loading and reaction temperature on hexadecanoic acid yield, assessing experimental reproducibility, and determining the statistical significance of the investigated process variables. This approach provides a basis for the valorisation of an underutilised biomass resource into a commercially relevant bio-based fatty acid under comparatively mild processing conditions.

The aim of this study is to investigate the production of hexadecanoic acid from *Gmelina arborea* leaf biomass through BaCl₂-catalysed thermal hydrolytic processing under relatively mild reaction conditions. Specifically, the study seeks to evaluate the effects of BaCl₂ catalyst loading and reaction temperature on the yield and specific yield of hexadecanoic acid; determine the optimum combination of catalyst concentration and reaction temperature for maximizing hexadecanoic acid production; assess the reproducibility and precision of the experimental process using duplicate measurements, standard deviation, coefficient of variation, and differences between replicate yields; and determine the statistical significance of the effects and interaction of catalyst loading and reaction temperature on hexadecanoic

acid production using two-way analysis of variance (ANOVA). The study ultimately aims to demonstrate the potential of *G. arborea* leaf biomass as an underutilised renewable feedstock for the production of value-added hexadecanoic acid through a simple aqueous catalytic thermal hydrolytic process.

2. Methods

Fresh *Gmelina arborea* leaves were harvested from the Kaduna Polytechnic campus, Kaduna, Nigeria, and air-dried under ambient laboratory conditions until a constant mass was achieved. The dried biomass was manually cleaned to eliminate foreign materials before being pulverised with a ceramic mortar and pestle. The resulting powder was sieved to obtain particle sizes of 250 and 300 μm in accordance with the procedure described by Ali and Ibrahim (2023).

The catalytic thermal hydrolytic synthesis was performed by dissolving 0.25 g of barium chloride (BaCl_2), corresponding to a catalyst concentration of 0.5 wt%, in 500 mL of distilled water contained in a 1000 mL conical flask. The reaction mixture was continuously agitated using a Gallenkamp hot-plate magnetic stirrer to ensure uniform catalyst dispersion. Thereafter, 50 g of the prepared *Gmelina arborea* leaf biomass was gradually introduced into the catalyst solution, and the flask was covered throughout the experiment to minimize heat loss and prevent external contamination.

The suspension was heated to the required reaction temperature 50 °C and maintained under continuous stirring for 30 min, following the methodology of Ibrahim *et al.* (2022). At the end of the reaction, the hot slurry was filtered successively through a clean muslin cloth and Whatman filter paper to remove unreacted solids. The filtrate was collected in a 1000 mL beaker and dehydrated using anhydrous magnesium sulphate. Phase separation of the dehydrated liquid was subsequently carried out with a separating funnel following the procedures reported by Ibrahim and Ali (2023) and Ibrahim *et al.* (2024). The recovered liquid product was weighed for yield determination, while all experiments were conducted in duplicate to evaluate experimental reproducibility.

The effects of reaction temperature and catalyst concentration on product formation were investigated by conducting the thermal hydrolytic process at 50, 60, 70, and 80 using a fixed BaCl_2 loading of 0.5 wt%. The experiments were then repeated under identical temperature conditions with an increased catalyst loading of 1.0 wt%, achieved by dissolving 0.50 g of BaCl_2 in 500 mL of distilled water. The dehydrated liquid products obtained from each experimental run were transferred into sterile 10 mL sample vials and submitted to the Central Research Laboratory, Afe Babalola University, Ado-Ekiti, Nigeria, for gas chromatography-mass spectrometry (GC-MS) analysis to identify and quantify the synthesized chemical constituents, following the analytical protocol described by Ibrahim *et al.* (2022). The resulting chromatographic profiles and mass spectra were subsequently processed and interpreted to determine the chemical composition of the products obtained from each reaction condition.

3. Results and Discussion

Table 1 presents the recovery products (g) and corresponding yields (%) of hexadecanoic acid obtained from BaCl_2 -catalysed thermal hydrolytic processing of *Gmelina arborea* leaf biomass at catalyst concentrations of 0.5 and 1.0% over the temperature range of 50-80 °C. Duplicate experimental runs were conducted to assess the reproducibility of the

process, and the average yield was calculated from the two measurements. The results demonstrate that both catalyst concentration and reaction temperature influenced the recovery of products and hexadecanoic acid yields.

Table 1. Recovery Products and Yields of Hexadecanoic Acid Obtained From BaCl₂-Catalysed Gmelina Arborea Leaf Biomass

Cat. (%)	Temp (°C)	Recovery Product Run 1 (g)	Recovery Product Run 2 (g)	Run 1 (%)	Run 2 (%)	Ave (%)
0.5	50	424.07	421.41	5.87	6.01	5.94
	60	344.94	343.31	4.66	4.80	4.73
	70	450.15	435.74	1.63	1.75	1.69
	80	460.70	435.71	1.42	1.56	1.49
1.0	50	430.30	426.45	5.85	5.99	5.92
	60	435.09	431.75	6.40	6.54	6.47
	70	427.41	425.35	6.96	7.10	7.03
	80	409.19	406.96	5.18	5.30	5.24

At a catalyst concentration of 0.5%, the average yield decreased progressively from 5.94% at 50 °C to 4.73% at 60 °C, followed by a substantial decline to 1.69% at 70 °C and 1.49% at 80 °C. The relatively high yield at 50 °C suggests that the lower temperature favoured the formation of hexadecanoic acid under this catalyst loading. The progressive reduction in yield at temperatures above 50 °C may be associated with enhanced secondary reactions, degradation, volatilization, or transformation of hexadecanoic acid and its precursors at elevated temperatures. At 1.0% BaCl₂, a different temperature-dependent behaviour was observed. The average yield increased from 5.92% at 50 °C to 6.47% at 60 °C, reaching a maximum of 7.03% at 70 °C, before decreasing to 5.24% at 80 °C. Thus, the optimum condition within the investigated range was 1.0% BaCl₂ at 70 °C, which produced an average hexadecanoic acid yield of 7.03%. This corresponds to an increase of approximately 18.3% relative to the 0.5% BaCl₂ treatment at the same temperature, where only 1.69% was obtained. The result indicates that increasing the catalyst concentration from 0.5 to 1.0% substantially improved the conversion or release of hexadecanoic acid at 60-70 °C.

The recovery-product data also provide useful information about the overall solid/liquid material recovered after processing. At 0.5% BaCl₂, the recovery product ranged from 343.31 to 460.70 g across the investigated temperatures, whereas at 1.0% BaCl₂ it ranged from 406.96 to 435.09 g. The recovery mass did not show a direct linear relationship with hexadecanoic acid yield. For example, the highest recovery product at 0.5% BaCl₂ occurred at 80 °C (460.70 g in Run 1), yet the corresponding hexadecanoic acid yield was only 1.42% in that run. This suggests that total recovered material should not be interpreted directly as the amount of target product, because the recovered fraction may contain unreacted biomass, other extractable compounds, catalyst-associated materials, and reaction products other than hexadecanoic acid.

The close agreement between the duplicate runs indicates generally good experimental reproducibility. The differences between Run 1 and Run 2 yields were relatively small, ranging from 0.14 to 0.15 percentage points for most treatments. The average yields therefore provide a reliable representation of the experimental performance. The maximum yield of 7.03% at 1.0% BaCl₂ and 70 °C demonstrates that an appropriate combination of

catalyst concentration and temperature is important for maximizing hexadecanoic acid production from *G. arborea* leaves. Thus, the results indicate that hexadecanoic acid production was strongly dependent on the interaction between BaCl₂ concentration and temperature. Increasing the catalyst concentration from 0.5 to 1.0% shifted the optimum temperature from 50 °C to 70 °C and increased the maximum average yield from 5.94 to 7.03%. However, the reduction in yield at 80 °C for both catalyst concentrations suggests that excessively high temperatures may adversely affect hexadecanoic acid recovery. The optimum experimental condition within the investigated range was therefore 1.0% BaCl₂ at 70 °C, providing an average yield of 7.03%.

Figure 1 illustrates the effect of reaction temperature on the specific yield of hexadecanoic acid obtained from BaCl₂-catalysed thermal hydrolytic processing of *Gmelina arborea* leaf biomass at catalyst concentrations of 0.5 and 1.0%. The figure compares the specific yields obtained from two experimental runs at reaction temperatures of 50, 60, 70, and 80 °C. The results show distinct temperature-dependent responses at the two catalyst concentrations.

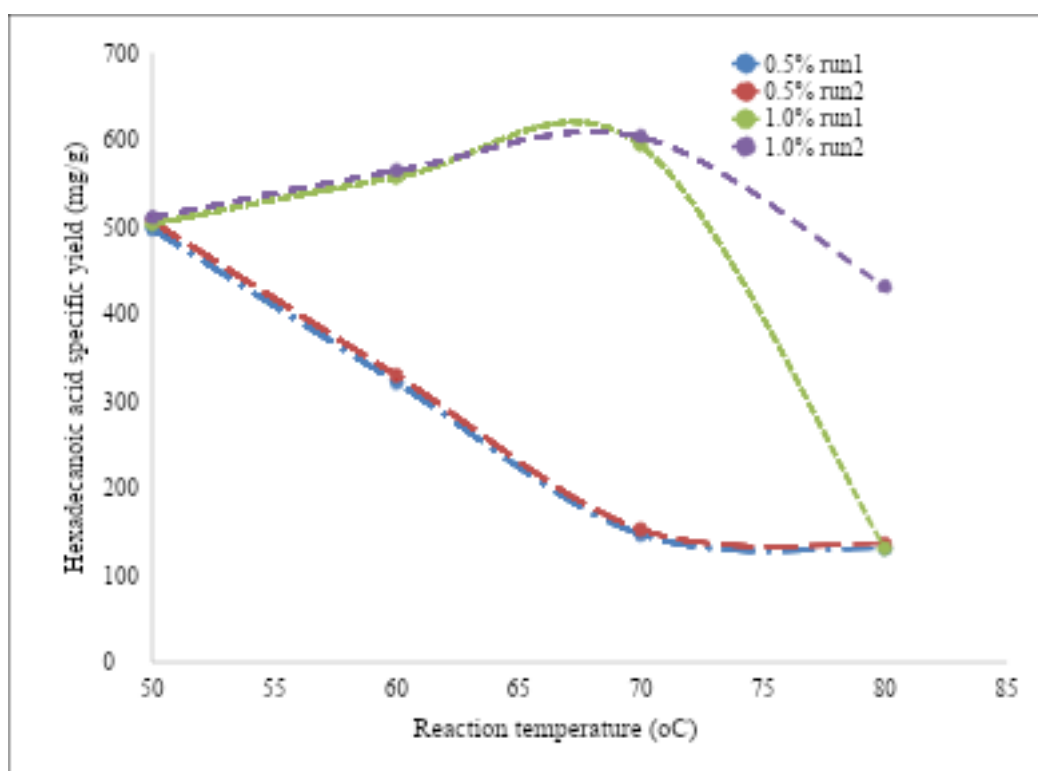


Figure 1. Effect of Reaction Temperature on the Specific Yield of Hexadecanoic Acid From *Gmelina Arborea* Leaf Biomass

At 0.5% BaCl₂, the specific yield decreased markedly with increasing reaction temperature. The yield was approximately 497-506 mg/g at 50 °C, decreased to approximately 145-150 mg/g at 70 °C, and remained relatively low at approximately 130-135 mg/g at 80 °C. The proximity of Run 1 and Run 2 throughout the temperature range indicates good agreement between the duplicate experiments. The sharp reduction in specific yield between 50 and 70 °C suggests that increasing the temperature beyond 50 °C was unfavourable for hexadecanoic acid production at the lower catalyst concentration. This behaviour may be associated with degradation or transformation of hexadecanoic acid or its precursors,

increased participation of the fatty acid in secondary reactions, or changes in the stability and recovery of the target compound at elevated temperatures. A markedly different response was observed at 1.0% BaCl₂. The specific yield increased from approximately 503–510 mg/g at 50 °C to about 600–610 mg/g at 70 °C, indicating that increasing the temperature from 50 to 70 °C enhanced hexadecanoic acid production under the higher catalyst loading. The maximum specific yield was therefore obtained at 70 °C with 1.0% BaCl₂, demonstrating that the combined effect of increased catalyst concentration and temperature favoured the release or formation of hexadecanoic acid from the leaf biomass.

However, a pronounced divergence between the two experimental runs was observed at 80 °C under 1.0% BaCl₂. Run 1 decreased sharply to approximately 130 mg/g, whereas Run 2 remained substantially higher at approximately 430–440 mg/g. This large difference indicates considerably greater experimental variability at this temperature and catalyst concentration. It may reflect sensitivity of the process to temperature control, heterogeneous distribution of the biomass or catalyst, sampling differences, or changes in product stability and recovery at the higher temperature. Nevertheless, the overall trend indicates that increasing the temperature beyond 70 °C did not provide a consistent improvement in hexadecanoic acid specific yield.

The contrasting profiles obtained at the two catalyst concentrations demonstrate the importance of catalyst loading–temperature interaction in the thermal hydrolytic conversion of *G. arborea* biomass. At 0.5% BaCl₂, the highest specific yield occurred at 50 °C, whereas increasing the catalyst concentration to 1.0% shifted the maximum yield to 70 °C. This suggests that the higher BaCl₂ concentration provided a more favourable catalytic environment for the release or conversion of hexadecanoic acid at the elevated temperature. The observation is consistent with the yield results presented in Table 1, where 1.0% BaCl₂ at 70 °C produced the highest average hexadecanoic acid yield (7.03%). Overall, Figure 2 demonstrates that 70 °C and 1.0% BaCl₂ represented the most favourable combination within the investigated conditions, giving the highest and most pronounced specific-yield response. Conversely, the relatively low yields obtained at higher temperatures under 0.5% BaCl₂ and the substantial run-to-run variation observed at 80 °C with 1.0% BaCl₂ suggest that further temperature increase is not advantageous. These findings reinforce the importance of optimizing both catalyst concentration and reaction temperature rather than increasing either parameter independently.

3.1. Reproducibility Analysis of Hexadecanoic Acid Yield

The reproducibility of the duplicate experimental runs was evaluated using the mean yield, standard deviation (SD), coefficient of variation (CV%), and the absolute difference between duplicate runs (Δ). The duplicate analyses demonstrated excellent reproducibility across all experimental conditions. The coefficients of variation ranged from 0.99 to 2.72%, well below the generally accepted limit of 5% for duplicate analytical measurements, indicating high precision and reliability of the experimental procedure as presented in Table 2. The coefficient of variation was calculated as in Equation 4:

$$CV (\%) = (SD/m) \times 100 \dots\dots\dots(4)$$

where (m) is the mean of the duplicate measurements.

Table 2. Reproducibility Analysis of the Specific Yield of Hexadecanoic Acid Produced from BaCl₂-Catalysed Thermal Hydrolysis of Gmelina Arborea Leaf Biomass

Catalyst Loading (%)	Temperature (°C)	Run 1 (mg/g)	Run 2 (mg/g)	Mean (mg/g)	Δ (mg/g)	SD (mg/g)	CV (%)
0.5	50	497.86	506.54	502.20	8.68	6.14	1.22
	60	321.48	329.58	325.53	8.10	5.73	1.76
	70	146.75	152.51	149.63	5.76	4.07	2.72
	80	130.84	135.94	133.39	5.10	3.61	2.71
1.0	50	503.45	510.89	507.17	7.44	5.26	1.04
	60	556.91	564.73	560.82	7.82	5.53	0.99
	70	594.96	604.00	599.48	9.04	6.39	1.07
	80	423.92	431.38	427.65	7.46	5.27	1.23

At the 0.5% BaCl₂ catalyst loading, the highest specific yield of hexadecanoic acid (502.20 mg/g) was obtained at 50°C, after which the yield declined markedly with increasing temperature to 325.53, 149.63, and 133.39 mg/g at 60, 70, and 80°C, respectively. Despite the substantial decrease in yield with temperature, the duplicate measurements remained highly consistent, with CV values between 1.22 and 2.72%. The slightly higher CVs observed at 70 and 80°C are expected because small absolute differences between duplicate measurements become proportionally larger when the mean yield is relatively low. For the 1.0% catalyst loading, reproducibility was even better, with CV values ranging from 0.99 to 1.23%. Increasing the catalyst loading from 0.5 to 1.0% substantially enhanced hexadecanoic acid production at higher temperatures. The yield increased from 507.17 mg/g at 50°C to a maximum of 599.48 mg/g at 70°C, before decreasing to 427.65 mg/g at 80°C. The maximum duplicate difference at this catalyst loading was only 9.04 mg/g, corresponding to a CV of 1.07%, demonstrating remarkable agreement between replicate experiments.

The consistently low standard deviations (3.61-6.39 mg/g) and narrow differences between duplicate runs (5.10-9.04 mg/g) confirm that the BaCl₂-catalysed thermal hydrolysis process is highly reproducible. Such precision indicates that the observed changes in hexadecanoic acid yield are primarily attributable to catalyst loading and reaction temperature rather than to experimental variability. Generally, the reproducibility analysis confirms that the analytical method and experimental protocol are robust. The low CV values (<3%) provide strong confidence in the reliability of the reported hexadecanoic acid yields and support the conclusion that 1.0% BaCl₂ at 70°C represents the optimum operating condition among the investigated temperatures, yielding 599.48 mg/g of hexadecanoic acid with excellent experimental precision.

3.2 Two-Way Analysis of Variance of Hexadecanoic acid specific yields

Using the duplicate measurements, the data can be analysed by two-way Analysis of Variance (ANOVA) to determine the effects of catalyst loading (0.5 and 1.0 wt.%) and reaction temperature (50-80 °C) on the specific yield of hexadecanoic acid. The two-way ANOVA indicates that both catalyst loading and reaction temperature exert statistically significant effects on the specific yield of hexadecanoic acid ($p < 0.0001$). Among the two main factors, temperature contributed the largest proportion of the total variation, closely followed by catalyst loading, as presented in Table 3, indicating that thermal conditions strongly influence

the release of hexadecanoic acid during BaCl₂-catalysed thermal hydrolysis of *Gmelina arborea* leaves.

Table 3. Two-Way Analysis of Variance Effects of Variable Factors on Hexadecanoic Acid Specific Yields

Source of Variation	df	Sum of Squares (SS)	Mean Square (MS)	F-value	p-value	Significance
Catalyst loading	1	235,812.84	235,812.84	3948.72	<0.0001	Highly significant
Temperature	3	370,485.61	123,495.20	2068.37	<0.0001	Highly significant
Catalyst × Temperature	3	236,504.17	78,834.72	1320.48	<0.0001	Highly significant
Error	8	477.82	59.73	—	—	—
Total	15	843,280.44	—	—	—	—

The interaction between catalyst loading and temperature was also highly significant ($p < 0.0001$), demonstrating that the influence of temperature depends on the catalyst loading employed. At 0.5 wt.% BaCl₂, increasing temperature from 50 to 80 °C progressively reduced the hexadecanoic acid yield (502.20 to 133.39 mg/g). In contrast, at 1.0 wt.% BaCl₂, the yield increased from 507.17 mg/g at 50 °C to a maximum of 599.48 mg/g at 70 °C before declining to 427.65 mg/g at 80 °C. This contrasting behaviour explains the strong interaction effect observed in the ANOVA. The residual (error) sum of squares was very small (SS = 477.82), reflecting the excellent agreement between duplicate experimental measurements. This is consistent with the previously calculated coefficients of variation (0.99-2.72%), confirming that experimental variability was minimal and that the observed differences in yield are attributable primarily to catalyst loading and reaction temperature rather than analytical error. Generally, the ANOVA demonstrates that 1.0 wt.% BaCl₂ combined with a reaction temperature of 70 °C provides the optimum condition for maximizing the production of hexadecanoic acid from *Gmelina arborea* leaf biomass. The highly significant interaction further suggests that catalyst loading and temperature should be optimized simultaneously rather than independently to achieve maximum product yield.

To the best of our knowledge, there are currently no published reports specifically describing the production yield of hexadecanoic acid from biomass-derived feedstocks under processing conditions comparable to those employed in the present study. The highest hexadecanoic acid yield obtained in this study was 7.10%, with a corresponding specific yield of 604.00 mg/g biomass, under optimum conditions of 1.0 wt% BaCl₂ catalyst loading, 70 °C reaction temperature, and 30 min reaction time using *Gmelina arborea* leaf biomass. Although the overall yield is relatively modest, the process offers important advantages because it operates under comparatively mild reaction conditions and utilizes an abundant, renewable, and low-cost biomass feedstock rather than fossil-derived resources.

The production of hexadecanoic acid through BaCl₂-catalysed thermal hydrolytic processing of *G. arborea* leaves represents a fundamentally different approach from the conventional saponification and acidification of palm oil. Conventional routes generally depend on vegetable oils, including edible oils, as feedstocks, which may compete with food production and raise concerns regarding food security and resource allocation. In contrast,

the present approach utilizes waste and underutilised lignocellulosic biomass, water as the reaction medium, a relatively simple inorganic catalyst, atmospheric pressure, and comparatively low reaction temperatures. These features enhance the attractiveness of the process from the perspectives of feedstock sustainability, process simplicity, and waste valorisation.

Importantly, the conversion of *G. arborea* leaf biomass into hexadecanoic acid provides a potential pathway for transforming an otherwise underutilised biological residue into a value-added bio-based chemical. This approach is consistent with the principles of the circular bioeconomy and sustainable production, particularly SDG 9 (Industry, Innovation and Infrastructure) through innovative biomass-conversion technologies and SDG 12 (Responsible Consumption and Production) through the valorisation of waste biomass and reduction of dependence on non-renewable feedstocks. It also has potential relevance to SDG 13 (Climate Action) by promoting renewable carbon resources and reducing reliance on fossil-derived raw materials.

Further optimization of catalyst loading, reaction temperature, reaction time, biomass particle size, and product recovery and selectivity could enhance hexadecanoic acid production and improve the overall process efficiency and economic viability. Consequently, BaCl₂-catalysed thermal hydrolytic processing of *G. arborea* leaves represents a promising and relatively mild route for converting renewable biomass into a commercially relevant bio-based molecule.

Conclusions

This study demonstrated the feasibility of converting *Gmelina arborea* leaf biomass into hexadecanoic acid through BaCl₂-catalysed thermal hydrolytic processing under comparatively mild reaction conditions. Both catalyst loading and reaction temperature substantially influenced hexadecanoic acid production, with their interaction also exerting a highly significant effect ($p < 0.0001$). At 0.5 wt.% BaCl₂, increasing the reaction temperature from 50 to 80 °C resulted in a progressive decline in specific hexadecanoic acid yield, whereas at 1.0 wt.% BaCl₂, the yield increased with temperature up to 70 °C before decreasing at 80 °C. The optimum condition within the investigated experimental range was therefore 1.0 wt.% BaCl₂ at 70 °C, which produced an average specific yield of 599.48 mg/g biomass, with the highest individual replicate reaching 604.00 mg/g. The low coefficients of variation (0.99–2.72%) and small differences between duplicate measurements confirmed good experimental reproducibility and provided confidence in the observed treatment effects. The two-way ANOVA further established that catalyst loading, reaction temperature, and their interaction were highly significant determinants of hexadecanoic acid production, demonstrating that these variables should be optimized simultaneously rather than independently.

Overall, the findings establish *G. arborea* leaves as a potentially useful and underutilised renewable feedstock for the recovery of a commercially relevant bio-based fatty acid. Compared with conventional approaches based primarily on triglyceride-rich oils, the investigated process offers the advantages of utilizing plant residue, employing water as the reaction medium, using a relatively simple inorganic catalyst, and operating at atmospheric pressure and comparatively low temperatures. These characteristics support the potential application of the process within a circular bioeconomy framework by transforming an underutilised biomass resource into a value-added chemical. The study therefore contributes to SDG 9 (Industry, Innovation and Infrastructure) through the development of a biomass-

conversion technology, SDG 12 (Responsible Consumption and Production) through waste valorisation and resource efficiency, and SDG 13 (Climate Action) through the potential substitution of conventional non-renewable feedstocks.

Nevertheless, the present investigation was limited to two BaCl₂ loadings and a restricted temperature range, and further work is required to establish the influence of reaction time, biomass particle size, catalyst concentration, biomass-to-liquid ratio, and product recovery conditions. Optimization of these parameters, together with assessment of product selectivity, catalyst recovery, process economics, and environmental performance, would be necessary to determine the scalability and commercial viability of the process. Thus, while the present results provide a useful proof of concept, they also establish a foundation for further development of sustainable hexadecanoic acid production from *G. arborea* leaf biomass.

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Conflicts of Interest

The authors declare no conflict of interest.

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