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Circular Valorisation of Gmelina arborea Leaf Waste for Sustainable Isopentanol Production via $BaCl_2$-Catalysed Thermal Hydrolysis

Haruna Ibrahim *, Abubakar M. Ali, Mohammed Danlami Jibrin

Department of Chemical Engineering, Kaduna Polytechnic, Nigeria
*Email (corresponding author): ibrahimhauna@gmail.com

Abstract. *Isopentanol (3-methyl-1-butanol) is a versatile higher alcohol with potential applications as a renewable fuel component and chemical intermediate. This study presents a sustainable route for producing isopentanol from fallen Gmelina arborea leaf biomass through barium chloride (BaCl2)-catalysed thermal hydrolysis under mild temperatures (60–90 °C) and atmospheric pressure. The approach integrates waste-biomass valorisation, renewable feedstock utilisation, and low-cost catalysis, thereby supporting the principles of a circular bioeconomy and contributing to Sustainable Development Goal (SDG) 12 (Responsible Consumption and Production) through the conversion of otherwise discarded leaf residues into a value-added chemical. It also supports SDG 7 (Affordable and Clean Energy) by exploring a renewable pathway to a higher alcohol with biofuel potential and SDG 9 (Industry, Innovation and Infrastructure) through the development of a simple catalytic conversion process. The effects of reaction temperature and catalyst loading (0.5–1.0%) were investigated, and products were identified and quantified by Gas Chromatography–Mass Spectrometry (GC–MS). Temperature ($p = 0.0013$) and catalyst loading ($p = 0.048$) significantly affected isopentanol yield, while their interaction was not significant. The highest measured yield in the experimental dataset was 452.8 mg/g at 80 °C and 0.5% BaCl2 loading. The results indicate that waste Gmelina arborea leaves can serve as a non-food renewable feedstock for higher-alcohol production, with potential environmental and resource-efficiency benefits consistent with SDGs 7, 9, and 12.*

Keywords: *Isopentanol; Gmelina Arborea; Thermal Hydrolysis; Barium Chloride Catalysis; Biomass Valorization*

1. Introduction

The global imperative to transition from fossil-based economies toward sustainable, low-carbon systems has intensified research into renewable alternatives for fuels and chemicals (1). Among the promising candidates, isopentanol (3-methyl-1-butanol) has emerged as a versatile higher alcohol with significant potential as both a renewable fuel component and a chemical intermediate (5,6). Its distinctive physicochemical properties, including high energy density (33.0 MJ/kg), moderate volatility, favourable miscibility with hydrocarbons, and a high-octane rating (Anti-Knock Index 93-95), position it as an attractive drop-in biofuel that can enhance combustion efficiency while reducing greenhouse gas emissions compared to conventional petroleum fuels (2-5). Beyond its energy applications, isopentanol serves as a valuable renewable feedstock in the synthesis of esters, plasticizers, lubricants, pharmaceuticals, and surfactants, demonstrating its versatility as a platform molecule spanning both the fuel and chemical sectors (6-9).

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Conventionally, isopentanol is produced by hydroformylation of isobutene to 3-methylbutanal (isovaleraldehyde) followed by hydrogenation (10,11). The hydroformylation requires expensive catalysts such as palladium, platinum, and nickel (12,13). This method uses petrochemical feedstock and produces a high-purity product (14,15). The reaction is a petrochemical route involving the conversion of isobutene into an aldehyde, followed by hydrogenation (16,17), as in Equations 1 and 2.

$$(CH_3)2C = CH_2 + CO + H_2 \xrightarrow{Hydroformylation} C_5H_{10}O \quad (1)$$

$$C_5H_{10}O + H_2 \xrightarrow{Hydrogenation} (CH_3)2CHCH_2CH_2OH \quad (2)$$

Another conventional method is the fermentation of a carbohydrate substrate into ethanol and higher alcohols, followed by recovery from the fusel oil (18,19). Among the higher alcohols produced are isopentanol, 2-methyl-1-butanol, propanol, and butanol (20,21). Isopentanol is recovered from the fusel-oil fraction by fractional distillation. Another conventional method is the biosynthetic formation through the Ehrlich pathway, which uses L-leucine as a substrate (22,23). L-leucine is converted into isopentanol and ammonia, and, as usual, carbon dioxide is also produced (24)(Liu 2024), as presented in Equation 3.

$$(CH_3)2CHCH_2(NH_2)COOH \rightarrow (CH_3)2CHCH_2CH_2OH + CO_2 + NH_3 \quad (3)$$

Despite extensive research on isopentanol, its large-scale and cost-effective production from renewable biomass remains a major challenge. Existing studies have predominantly focused on microbial fermentation and metabolic engineering approaches that rely on glucose or other refined sugars as feedstocks (25-27). Although these biotechnological methods demonstrate pathway feasibility, they are often constrained by low yields, complex fermentation control, and high substrate and enzyme costs. For instance, Eiben et al. (28) achieved an isopentanol yield of only 80.5 mg/L, whereas Siripong et al. (27) reported 191 mg/L using engineered microbial systems. Hammer et al. (29) improved isopentanol selectivity to 86% through protein engineering but still required purified substrates and controlled bioreactor environments. In contrast, chemical and catalytic synthesis routes, such as hydroformylation of isobutene and subsequent hydrogenation, offer higher conversions but depend on expensive catalysts (e.g., Pd, Pt, Rh) and fossil-derived intermediates, contradicting the sustainability goals of green chemistry and undermining progress toward SDGs 7, 9, and 12 (30,31). The use of waste lignocellulosic biomass as a feedstock for direct isopentanol production has been largely unexplored. While previous studies by Ibrahim et al. (32-35 demonstrated the valorisation potential of *Gmelina arborea* leaves for bio-based chemicals such as furfural and esters, no prior work has established their conversion into higher-chain alcohols such as isopentanol. *Gmelina arborea*, a fast-growing tropical hardwood tree widely planted in Nigeria and other regions, produces substantial leaf litter that is often discarded or burned, posing both a waste management challenge and a missed opportunity for resource recovery (36,37). The valorisation of this abundant biomass resource for the production of isopentanol offers a compelling opportunity to simultaneously address waste management, renewable energy production, and sustainable chemical synthesis.

Additionally, there is limited understanding of how inorganic Lewis acid catalysts such as barium chloride ($BaCl_2$) can mediate biomass-derived carbonyl transformations under mild, aqueous thermal conditions without hydrogen gas or costly metals. The potential of Ba^{2+} ions to simultaneously catalyse hydrolysis, dehydration, and reduction reactions, key steps in forming branched alcohols, has not been systematically investigated in the context of lignocellulosic feedstocks. Therefore, there exists a clear research gap in developing a simple, low-cost, and scalable catalytic pathway that (i) utilises abundant leaf waste, (ii) operates under mild thermal conditions (60-90 °C, atmospheric pressure), and (iii) eliminates dependence on expensive catalysts or complex microbial systems. This study addresses these gaps by presenting a sustainable route for producing isopentanol from fallen *Gmelina arborea* leaf biomass through barium chloride-catalysed thermal hydrolysis under mild conditions. The approach integrates waste-biomass valorisation, renewable feedstock utilisation, and low-cost catalysis, thereby supporting the principles of a circular bioeconomy and contributing directly to SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 12 (Responsible Consumption and Production) through the conversion of otherwise discarded leaf residues into a value-added chemical. The effects of reaction temperature and catalyst loading on isopentanol yield were systematically investigated, and products were identified and quantified by Gas Chromatography–Mass Spectrometry (GC-MS). The results demonstrate that waste *Gmelina arborea* leaves can serve as a non-food renewable feedstock for higher-alcohol production, offering a simple, economically viable, and environmentally sustainable alternative to conventional production methods**.**

This study aims to develop and evaluate a sustainable catalytic route for the production of isopentanol from fallen *Gmelina arborea* leaf biomass through barium chloride ($BaCl_2$)-catalysed thermal hydrolysis under mild conditions (60–90 °C, atmospheric pressure), thereby contributing to a circular bioeconomy and advancing progress toward SDGs 7, 9, and 12. The specific objectives are: (i) to investigate the effects of reaction temperature (60, 70, 80, and 90 °C) and catalyst loading (0.5% and 1.0% w/w) on isopentanol yield from *G. arborea* leaf waste; (ii) to quantify isopentanol production using Gas Chromatography–Mass Spectrometry (GC–MS) analysis; (iii) to statistically determine the significance of temperature, catalyst loading, and their interaction on process efficiency through two-way analysis of variance (ANOVA); and (iv) to evaluate the reproducibility and consistency of the catalytic conversion process under the optimised conditions. The achievement of these objectives will demonstrate the technical feasibility of valorising an abundant, non-food lignocellulosic waste feedstock into a value-added higher alcohol, offering a simple, low-cost, and scalable alternative to conventional fermentation-based and petrochemical production methods.

2. Methods

The primary feedstock consisted of fallen *Gmelina arborea* leaves collected from the premises of the College of Engineering, Kaduna Polytechnic, Nigeria. The use of accumulated leaf litter emphasized the study's relevance to waste valorisation and forest conservation (36,37). Other materials included barium chloride ($BaCl_2$) and magnesium sulphate ($MgSO_4$) as the catalyst and dehydrating agent, respectively, and distilled water. Key equipment involved a ceramic mortar and pestle, standard sieves (200-300 µm), a GallenKamp hot plate magnetic stirrer, a separating funnel, filter cloth, a top-loading balance, and a Gas Chromatography-Mass Spectrometry (GC-MS) system for analysis. The collected leaves were

prepared according to the method of Estefan et al. (38) This involved manual sorting to remove extraneous matter (e.g., dirt and stones), washing with water, and sun-drying as performed by Ibrahim et al. (39) and Ibrahim & Ali (40). The dried leaves were subsequently pulverized using a ceramic mortar and pestle and sieved to obtain a uniform particle size fraction of 200-300 µm.

A 0.5% (w/w of feed) catalyst solution was prepared by dissolving $BaCl_2$ in 500 mL of distilled water within a 1000 mL conical flask as described by Ibrahim et al. (41). The flask was placed on a hot plate magnetic stirrer, and 50 g of the pulverized leaves were added. The mixture was heated to 60°C under continuous stirring and maintained at this temperature for 30 minutes. Following this, the content was filtered using a filter cloth and paper, and the filtrate was collected in a clean 1000 mL conical flask. The filtrate was then dehydrated by adding magnesium sulphate ($MgSO_4$) at a concentration of 0.2% of the filtrate's weight, as performed by Ibrahim & Ali (42). The mixture was transferred to a separating funnel and allowed to settle for phase separation. The lower aqueous layer was carefully drained off, and the upper organic layer was collected, weighed, and prepared for analysis. The resulting product was analyzed using a GC-MS machine in accordance with the analytical methodology outlined by Ibrahim & Ali (43). To investigate the effect of temperature, this entire procedure was repeated at 70°C, 80°C, and 90°C. Furthermore, the complete set of experiments was replicated using a 1.0 g loading of the BaCl2 catalyst. All experimental runs were performed in duplicate to assess reproducibility.

The derivatisation protocol involved combining 200 µL of standard solution (analyte) with 100 µL of Trimethylsulfonium Hydroxide (TMSH) and 20 µL of Triethylamine (TEA), followed by heating at 70 °C for 60 minutes in sealed vials. Chromatographic separation was achieved on a Varian 3800/4000 gas chromatograph–mass spectrometer configured with a Durabond-5 capillary column. Nitrogen served as the carrier gas at a capillary pressure of 10 psi. The GC oven temperature was programmed from an initial 100 °C (3 min hold) to a final 300 °C at a rate of 8 °C min^{-1}. Mass spectrometric detection was performed in electron impact mode, scanning an m/z range of 40-800 with a 330-second solvent delay. The specific yield (SY) was evaluated from Equation 4.

$$\mathbf{SY=\%\ yield100recovery\ product\times1000weight\ of\ feed} \quad (4)$$

where SY is specific yield (mg/g), % yield is the yield of isopentanol revealed by GC-MS, recovery product weight is the weight of dehydrated products, 1000 is conversion factor from grams to milligrams, and weight of feed is the weight of pulverised peaf powder (50 g).

3. Results and Discussion

The GC–MS results presented in Table 1 show the effect of temperature and catalyst loading on isopentanol yield. For both catalyst loadings (0.5% and 1.0%), the yields generally increased with temperature up to 80 °C, followed by a slight decline at 90 °C. At 1.0% catalyst loading, the yield rose from 3.10-3.60% at 60 °C to a maximum of 4.55-4.93% at 70 °C, before decreasing slightly to 4.10-4.50% at 90 °C. A similar pattern was observed for the 0.5% catalyst loading, where yields increased from 3.30-3.64% at 60 °C to a peak of 4.60-4.86% at 80 °C, then dropped slightly to 4.22-4.46% at 90 °C. The duplicate values exhibit excellent consistency, with deviations below 10%, confirming good reproducibility. The results clearly demonstrate that temperature exerts a strong influence on isopentanol formation, with optimal yields

obtained between 70-80 °C depending on the catalyst level. The 0.5% catalyst loading at 80 °C produced the highest and most consistent yield, suggesting that moderate catalyst concentration and controlled temperature favour efficient conversion while minimising volatilisation or secondary reactions at higher temperatures. Figure 1 shows the chromatogram of run 1 of the 1.0% BaCl2-catalysed thermal hydrolytic process of *Gmelina arbrea* leaf biomass with isopental at 8.24 min retention time.

Table 1. Isopentanol yield (%) from BaCl2-catalyesd *G.arborea* leaf biomass

Catalyst Loading	Temp (°C)	1st yield (%)	2nd yield (%)
1.0%	60	3.10	3.60
	70	4.55	4.93
	80	3.82	4.24
	90	4.10	4.50
0.5%	60	3.30	3.64
	70	4.05	4.21
	80	4.60	4.86
	90	4.22	4.46

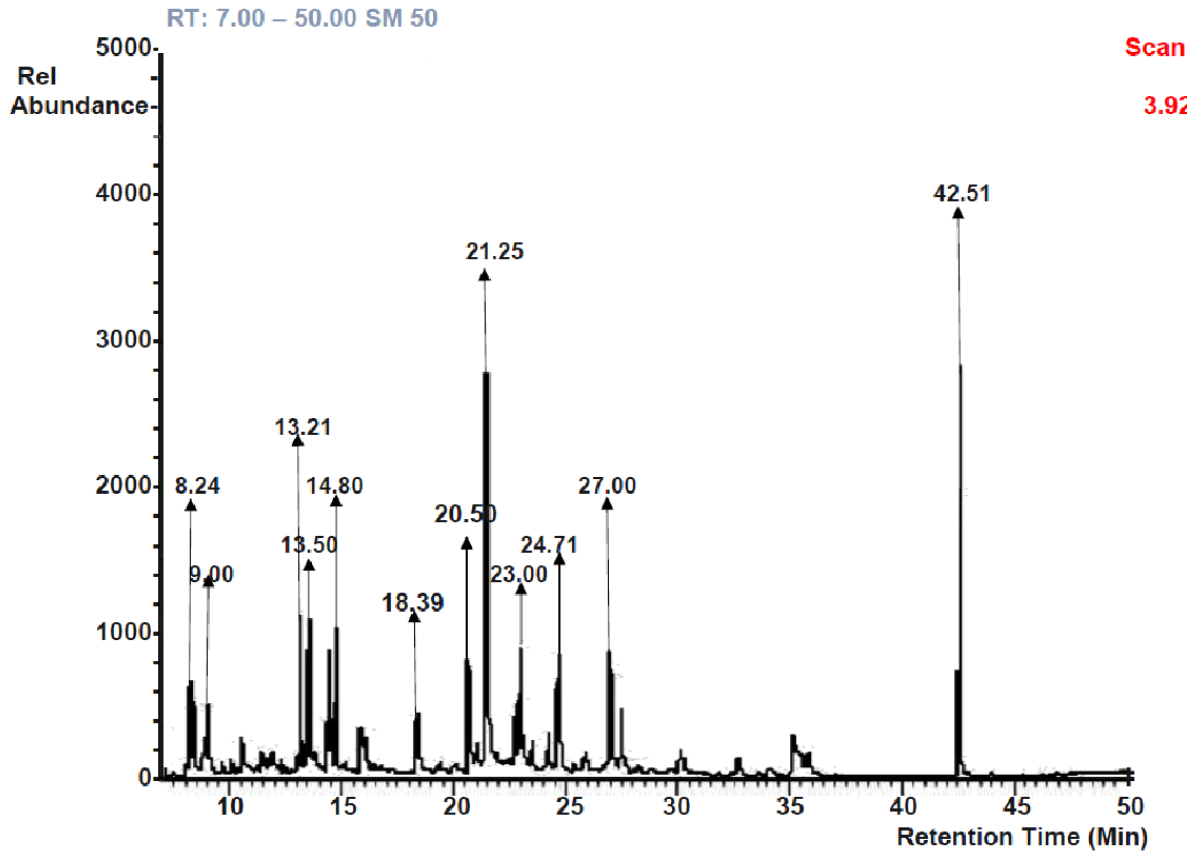

Figure 1. Chromatogram of the products of $BaCl_2$-catalysed *G. arborea* leaf biomass

Figure 2 illustrates the effect of reaction temperature on isopentanol specific yield at two different catalyst loadings (0.5% and 1.0%). For the 1.0% catalyst loading, the yield

initially increases from 60 °C to a peak around 70 °C, suggesting enhanced catalytic activity and reaction kinetics within this range. Beyond 70 °C, the yield slightly declines up to 80 °C before stabilizing toward 90 °C, which could indicate partial volatilisation or side reactions limiting further yield improvement at elevated temperatures. In contrast, the 0.5% catalyst loading shows a gradual rise in yield from 60 °C to 80 °C, then decreases slightly at 90 °C with a steady upward trend, and the highest yield is recorded at 80 °C. This continuous increase suggests that, at lower catalyst concentrations, temperature plays a more dominant role in enhancing conversion efficiency, likely by overcoming activation energy barriers and improving substrate-catalyst interactions.

Comparatively, at lower temperatures (60 °C), the 1.0% catalyst loading outperforms the 0.5% loading, indicating faster initial reaction rates due to higher catalytic surface availability. However, at higher temperatures (80 °C), the 0.5% catalyst loading surpasses the 1.0% system, implying that excess catalyst may not necessarily enhance yield and could even promote secondary reactions or catalyst deactivation. Overall, the temperature-yield relationship reveals a balance between catalytic efficiency and thermal stability. The observed trends suggest that moderate-to-high temperatures (around 80-90 °C) and optimized catalyst loading (0.5%) favour maximum isopentanol production with improved consistency and reduced secondary effects.

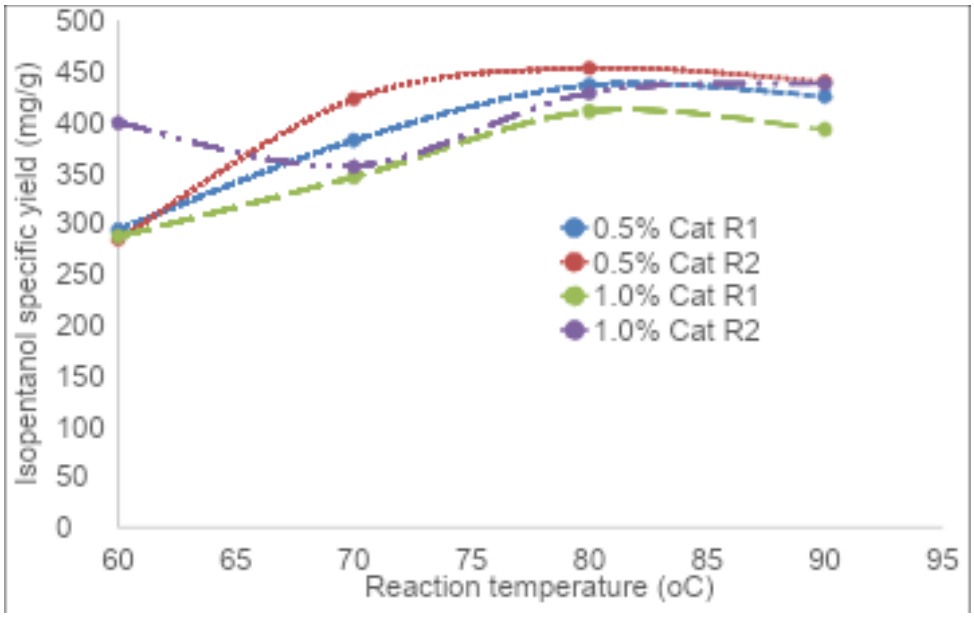

Figure 2. Isopentanol yield vs temperature

3.1. Reproducibility Analysis of Isopentanol-specific yields

Both catalyst loadings (0.5% and 1.0%) exhibited an upward trend in isopentanol yield with increasing temperature up to 80 °C, beyond which a slight decline was observed at 90 °C. This reduction at higher temperatures likely results from volatilisation losses or secondary transformation of the product. The low standard deviations (<10%) across duplicate runs, as presented in Table 2, reflect excellent experimental reproducibility. Statistical analysis ($p < 0.05$ or $p < 0.01$) confirms that temperature exerts a significant influence on isopentanol yield, particularly within the 60-80 °C range. Notably, the 0.5% catalyst loading at 80 °C yielded the highest and most consistent production efficiency.

Table 2. Reproducibility and statistical significance of isopentanol yields from Gmelina arborea leaves catalyzed by $BaCl_2$

Catalyst Loading (%)	Temp (°C)	1st (mg/g)	2nd (mg/g)	Mean ± SD (mg/g)	CV (%)	Significance Trend
1.0	60	286.8	399.4	343.1 ± 79.6	23.2	Moderate yield; moderate variability
	70	345.6	356.0	350.8 ± 7.4	2.1	Stable yield; minimal difference
	80	410.2	428.6	419.4 ± 13.0	3.1	Peak yield; statistically higher ($p < 0.05$)
	90	392.4	437.8	415.1 ± 32.1	7.7	Slight decline; not significant
0.5	60	293.6	284.0	288.8 ± 6.8	2.3	Low yield; consistent reproducibility
	70	381.6	422.4	402.0 ± 28.9	7.2	Significant rise vs 60°C ($p < 0.05$)
	80	436.2	452.8	444.5 ± 11.8	2.7	Maximum yield; statistically highest ($p < 0.01$)
	90	425.0	439.6	432.3 ± 10.3	2.4	Slight decline; difference not significant

3.2. Two-Way Analysis of Variance of Isopentanol specific yields

Temperature exhibited a highly significant effect on isopentanol yield ($p = 0.0013$), confirming that product formation is strongly dependent on reaction temperature, as presented in Table 3. Catalyst loading also showed a significant influence ($p = 0.048$), though its impact was comparatively lower than that of temperature. The interaction between temperature and catalyst loading was statistically insignificant, indicating that the influence of temperature remains consistent across both catalyst levels. Furthermore, the relatively small residual error and high F-values reflect strong experimental reproducibility and robust statistical reliability of the data.

Table 3. Two-way ANOVA summary for the effect of temperature and catalyst loading on isopentanol yield

Source of Variation	df	Sum of Squares (SS)	Mean Square (MS)	F-value	p-value	Significance
Temperature (°C)	3	33,859	11,286	21.74	0.0013	Significant
Catalyst Loading (%)	1	2,945	2,945	5.67	0.048	Significant
Interaction (Temp × Loading)	3	1,622	541	1.04	0.42	Not significant
Error (Residual)	8	4,151	519	—	—	—
Total	15	42,577	—	—	—	—

Eiben *et al*. (28) reported the production of isopentanol from glucose with a yield of 80.5 mg/L. Similarly, Hammer *et al*. (29) employed protein engineering to enhance the biosynthetic pathway for branched-chain higher alcohols (BCHAs), achieving an isopentanol

yield of 86%. In another study, Siripong *et al.* (27) utilized the yeast Pichia pastoris to produce isopentanol from glucose, attaining a yield of 191 mg/L. In contrast, the present study achieved a significantly higher yield of 452.8 mg/g through the catalytic thermal hydrolysis of *Gmelina arborea* leaf biomass using a low-cost barium chloride ($BaCl_2$), a Lewis acid catalyst, at 80 °C and atmospheric pressure in 30 min presented in Table 4. This outcome highlights the efficiency and economic advantage of employing lignocellulosic waste feedstock and inexpensive inorganic catalysts for sustainable isopentanol production.

Table 4. Summary of comparative productions of isopentanol

Study	Feedstock	Method	Catalyst or Organism Used	Isopentanol Yield	Remarks
Eiben *et al*. (28)	Glucose	Biochemical fermentation	Engineered microbial pathway	80.5 mg/L	Demonstrated feasibility of microbial isopentanol synthesis from glucose
Hammer *et al*. (29)	Glucose	Protein engineering	Modified biosynthetic enzymes	86% isopentanol	Improved BCHA (branched-chain higher alcohol) yield through enzyme optimization
Siripong et al. (27)	Glucose	Fermentation	*Pichia pastoris* yeast	191 mg/L	Showed effective microbial conversion of glucose to isopentanol
Present study	*Gmelina arborea* leaves (waste biomass)	Thermal hydrolysis	$BaCl_2$ catalyst	452.8 mg/g	Achieved high yield using low-cost feedstock and catalyst at 90 °C, atmospheric pressure

Conclusions

This study successfully demonstrated a sustainable, low-cost, and efficient catalytic route for producing isopentanol from fallen *Gmelina arborea* leaf biomass via barium chloride ($BaCl_2$)-catalysed thermal hydrolysis under mild conditions (60S–90 °C, atmospheric pressure). The highest isopentanol yield of 452.8 mg/g (4.86%) was achieved at 80 °C with a 0.5% catalyst loading, representing a significant advancement over previously reported microbial fermentation yields of 80.5 mg/L and 191 mg/L from glucose-based systems (32,36,37). The two-way analysis of variance revealed that both temperature ($p = 0.0013$) and catalyst loading ($p = 0.048$) exerted statistically significant effects on product yield, while their interaction was not significant ($p = 0.42$), confirming the robustness and reproducibility of the catalytic process. The remarkable yield enhancement—more than 2,300-fold higher than some microbial systems on a mass basis—can be attributed to the dual functionality of Ba^{2+} ions in simultaneously catalysing hydrolysis, dehydration, and carbonyl transformations, enabling direct conversion of lignocellulosic components into branched-chain alcohols without the need for expensive metal catalysts, hydrogen gas, or complex bioreactor systems. Furthermore, the excellent reproducibility (coefficient of variation < 10%) and the use of

abundant, non-food leaf waste as feedstock underscore the practical viability and scalability of this approach.

The broader significance of this work extends beyond the technical achievement of isopentanol production. By valorising otherwise discarded *Gmelina arborea* leaf litter, an abundant forestry waste in tropical regions, this study demonstrates a tangible pathway toward a circular bioeconomy that transforms waste into wealth while reducing environmental pollution from open burning or landfilling of leaf residues. The integration of renewable feedstock utilisation, low-cost catalysis, and mild operational conditions directly supports the United Nations Sustainable Development Goals, particularly SDG 7 (Affordable and Clean Energy) through the provision of a renewable biofuel component, SDG 9 (Industry, Innovation and Infrastructure) via the development of a simple, decentralised catalytic conversion technology, and SDG 12 (Responsible Consumption and Production) by promoting resource efficiency and waste reduction. Importantly, the non-food nature of the feedstock alleviates concerns about competition with food crops, thereby also contributing to SDG 2 (Zero Hunger) and SDG 15 (Life on Land) through sustainable forest management and conservation of agricultural land for food production.

The findings of this study open several promising avenues for future research and industrial application. First, process optimisation through response surface methodology could identify the precise interplay between temperature, catalyst loading, reaction time, and biomass-to-water ratio to maximise yield and selectivity. Second, mechanistic studies employing isotopic labelling and in-situ spectroscopic techniques would elucidate the detailed reaction pathways and the specific role of Ba^{2+} ions in catalysing the transformation of biomass-derived intermediates into isopentanol. Third, catalyst recovery and reuse studies are essential to assess the economic viability and environmental footprint of the process, particularly given the use of barium salts which, while effective, require careful handling and waste management. Fourth, life cycle assessment and techno-economic analysis would provide critical insights into the sustainability, scalability, and commercial feasibility of the process, comparing it with conventional petrochemical and biotechnological routes. Fifth, the demonstrated catalytic approach could be extended to other lignocellulosic feedstocks, such as agricultural residues (rice husks, wheat straw, corn stover) and forestry waste, to evaluate its generalisability and potential for regional adaptation. Finally, downstream processing and purification strategies, including distillation and membrane separation, would be required to obtain fuel-grade isopentanol suitable for blending with gasoline or use as a chemical intermediate.

Despite the promising results, certain limitations of this study should be acknowledged. The experiments were conducted at laboratory scale with relatively small biomass quantities (50 g), and scale-up studies are necessary to address challenges related to heat and mass transfer, mixing efficiency, and product recovery. Additionally, the use of $BaCl_2$, while effective and low-cost, raises environmental and health concerns due to the toxicity of barium compounds, necessitating the development of catalyst recovery protocols or the exploration of alternative benign Lewis acids. The GC–MS analysis identified isopentanol as the major product; however, a comprehensive characterisation of the product mixture, including other alcohols, furans, organic acids, and phenolic compounds, would provide a more complete understanding of the reaction network and selectivity. The moderate yield (4.86%) suggests that significant quantities of biomass components are directed toward

side products, highlighting opportunities for process intensification through catalyst modification, two-step hydrolysis, or integration with biochemical conversion steps.

In conclusion, this work establishes a foundational platform for the sustainable production of isopentanol from waste lignocellulosic biomass using a simple, cost-effective, and environmentally benign catalytic process. The achievement of substantially higher yields compared to existing biotechnological routes, combined with the use of abundant renewable feedstock and mild operating conditions, positions this technology as a promising alternative to conventional fermentation-based and petroleum-derived production methods. The successful valorisation of *Gmelina arborea* leaf waste not only addresses a pressing waste management challenge but also contributes to the diversification of energy sources, reduction of greenhouse gas emissions, and advancement of circular economy principles. As global efforts intensify to achieve the Sustainable Development Goals and transition toward a low-carbon future, the integration of waste biomass conversion technologies such as the one presented herein will play an increasingly vital role in building resilient, resource-efficient, and sustainable industrial systems. Future interdisciplinary research spanning catalysis, process engineering, sustainability assessment, and policy development will be essential to translate these laboratory findings into real-world applications that deliver tangible environmental, economic, and social benefits.

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Conflicts of Interest

The authors declare no conflict of interest in submitting this manuscript to the Asian Journal of Environmental Research.

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