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Optimized lithium-impregnated silica catalyst from corn cob waste for enhanced biodiesel production: Structural tuning and circular economy application

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ABSTRACT

The transformation of agricultural waste into high-performance catalytic materials represents a promising route toward sustainable energy production. This study investigates the synthesis, structural characterization, and catalytic evaluation of lithium-impregnated silica derived from corn cob ash for biodiesel production. The silica was extracted through calcination and acid leaching, then impregnated with LiOH and calcined at 350 °C, 450 °C, 550 °C, and 650 °C. Comprehensive analyses using FTIR, XRD, SEM–EDS, and GC–MS confirmed the formation of Si–O–Li bonds and lithium silicate phases with optimal surface morphology. The catalyst calcined at 550 °C exhibited the highest biodiesel yield of 85%, attributed to a Li_2O content of 17.90% and a structurally balanced amorphous-crystalline framework. The RBD palm oil feedstock showed ideal conditions (FFA: 0.15%; moisture: 0.07%), and the triglyceride profile supported efficient base-catalyzed transesterification. Compared to traditional CaO or homogeneous alkali systems, the lithium-modified catalyst demonstrated superior reusability, stability, and reduced leaching. This work exemplifies how circular economy strategies can be integrated into catalyst design by valorizing biomass into functional materials for green fuel technologies.

Keywords: lithium silica catalyst, corn cob ash, biodiesel, transesterification, circular economy.

INTRODUCTION

The transition toward sustainable energy systems and effective biomass utilization has underscored the importance of exploring renewable resources for industrial applications. Among these, biodiesel has emerged as a critical component in reducing dependence on fossil fuels. However, the production of biodiesel requires efficient, environmentally benign, and cost-effective catalysts. In this regard, agricultural residues, particularly corn cobs, offer an attractive solution due to their abundance, low cost, and high silica content (Shim et al., 2015). The conversion of corn cob waste into silica not only addresses environmental concerns related to biomass disposal but also aligns with the principles of the circular economy by transforming agricultural waste into high-value catalytic materials (Mo et al., 2008). Corn cob-derived silica possesses intrinsic porosity and surface properties suitable for catalytic applications, especially in transesterification reactions crucial for biodiesel production (Dhaneswara et al., 2023).

Despite the environmental advantages of utilizing biomass-derived catalysts, the current catalyst systems in biodiesel production present substantial limitations. Homogeneous base catalysts such as NaOH and KOH, while catalytically efficient, generate large amounts of soap and alkaline wastewater, complicating product purification and increasing operational costs (Yanti et al., 2019). These catalysts are also non-reusable, limiting their sustainability. On the other hand, heterogeneous catalysts derived from agricultural waste mitigate some of these issues but often lack the thermal and mechanical stability required for industrial operations, especially under methanol-rich and high-temperature conditions (Permatasari et al., 2016; Fatimah et al., 2023).

Recent advances suggest that lithium incorporation into silica frameworks can offer a promising pathway to address these challenges. Lithium catalysts exhibit high basicity but are known to suffer from significant leaching in polar solvents like methanol during biodiesel transesterification (Pal et al., 2014; Chen et al., 2014). Immobilizing lithium ions on silica supports – especially those derived from biomass like corn cobs – can enhance structural integrity and reduce leaching. The formation of Si–O–Li bonds increases the mechanical strength of the catalyst and stabilizes lithium under reactive conditions (Rahadi et al., 2021; Morales et al., 2011). These bonds also improve basicity, facilitating higher biodiesel conversion rates by promoting efficient alcohol deprotonation and nucleophilic attack mechanisms required in transesterification (Björk et al., 2017).

While silica from corn cobs has been successfully synthesized and applied as a heterogeneous catalyst support, challenges remain. Studies show that mesoporous silica materials often suffer from structural degradation and mass transfer limitations at temperatures above 600 °C, leading to reduced porosity and active site availability (Zapelini et al., 2018; Zhang et al., 2019). Moreover, the presence of impurities and the amorphous nature of biomass-derived silica can influence its catalytic performance under thermal stress (Al-Muhtaseb et al., 2022). Furthermore, although some research has explored lithium-functionalized silica systems, comprehensive evaluations that directly link lithium loading, catalyst structure, and performance, particularly using corn cob-derived silica, remain scarce. This highlights a critical research gap in understanding the structure–activity relationships that govern the efficacy of lithium-modified catalysts in biodiesel synthesis.

This study aims to develop a sustainable, high-performance lithium-impregnated silica catalyst derived from corn cob waste and investigate its structural properties and catalytic performance in biodiesel production. The hypothesis is that lithium immobilization on corn cob–derived silica will result in the formation of stable Si–O–Li linkages, enhancing the catalyst's thermal and mechanical stability, reducing lithium leaching, and increasing its basicity. This will, in turn, improve the overall efficiency and reusability of the catalyst. The novelty of this research lies in its integrated approach: combining agricultural waste valorization, advanced material synthesis, and performance evaluation within a circular economy framework. The study not only contributes to the field of green catalysis but also provides scalable and environmentally conscious solutions for biodiesel production, supporting sustainable development and local economic growth through waste utilization (Dias et al., 2021; Aguado-Deblas et al., 2020).

METHODOLOGY

Materials

Corn cobs were sourced from agricultural waste in Deli Serdang, North Sumatra, Indonesia. The biomass was cleaned using deionized water to eliminate surface contaminants and oven-dried at 100 °C for 6 hours to remove moisture. The feedstock for biodiesel synthesis was refined, bleached, and deodorized palm oil (RBDPO), characterized by a free fatty acid (FFA) content of 0.05% to 0.15% and a moisture level between 0.07% and 0.08%. Analytical-grade chemicals, including hydrochloric acid (37%), lithium hydroxide (99%), and methanol (99.99%), were procured from Sigma-Aldrich.

Preparation of corn cob ash (silica source)

Dried corn cobs were ground and sieved to obtain particles with a size of 60 mesh. The resulting powder was subjected to calcination in a muffle furnace at 650 °C for 4 hours to remove organic content and obtain silica-rich ash. This temperature was chosen based on findings that calcination between 500–650 °C preserves silica structure while ensuring purity (Shim et al., 2015). Post-calcination, the ash was treated with 1 M HCl in a solid-to-liquid ratio of 1:6 (30 g ash in 180 mL acid) to remove residual metal oxides and enhance silica quality (Su and Guo, 2014). The acid-leached sample was rinsed with distilled water and dried at 105 °C for 3 hours to yield purified amorphous silica.

Synthesis of lithium-impregnated silica catalyst

The lithium-based catalyst was synthesized via wet impregnation. The purified silica was dispersed in distilled water, and a LiOH solution was introduced dropwise to achieve a molar ratio of LiOH:silica at 2:1. This ratio was selected to promote uniform lithium distribution and maximize Si–O–Li bond formation without significant aggregation (Kulkarni et al., 2006; Li and Zhang, 2015). The suspension was stirred at 70 °C for 3 hours at 250 rpm, followed by drying at 150 °C for 1 hour. Calcination was carried out at 350 °C, 450 °C, and 550 °C for 1 hour each to evaluate phase changes and optimize catalyst stability.

Catalyst characterization

X-ray diffraction (XRD) with Cu Kα radiation (40 kV, 30 mA) was used to identify crystalline phases and confirm lithium incorporation (Su and Guo, 2014). Fourier-transform infrared spectroscopy (FTIR) in the range of 450–4000 cm^{-1} detected functional groups and Si–O–Li bond formation (Kulkarni et al., 2006). Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) assessed the catalyst's surface morphology and elemental composition, verifying lithium dispersion (Fatimah et al., 2023). Gas chromatography-mass spectrometry (GC–MS) quantified fatty acid methyl esters (FAMEs) produced in transesterification (Putra et al., 2020).

Transesterification process and biodiesel analysis

The transesterification reaction was conducted in a three-necked batch reactor at 65 °C with 300 rpm stirring. A catalyst loading of 3 wt% relative to oil and a methanol-to-oil molar ratio of 12:1 were employed. These parameters were chosen based on optimal yields reported for lithium-based catalysts while minimizing leaching (Chen et al., 2007; Serio et al., 2007). The reaction proceeded for 1 hour, after which the catalyst was removed via filtration. The biodiesel phase was washed with 500 mL distilled water and heated at 105 °C to evaporate residual methanol. Biodiesel quality was verified according to ASTM D6751 and EN 14214 standards.

RESULTS AND DISCUSSION

FTIR analysis

Fourier-transform infrared spectroscopy (FTIR) analysis revealed key transformations in the chemical structure of corn cob-derived silica catalysts modified with lithium and calcined at different temperatures. From Figure 1. In the untreated corn cob ash sample, broad O–H stretching bands were observed between 3400 and 3200 cm^{-1}, attributed to silanol (Si–OH) groups and adsorbed moisture. Upon lithium impregnation and progressive calcination at 350 °C, 450 °C, and 650 °C, these O–H bands decreased in intensity, confirming the thermal dehydration and structural condensation of hydroxyl groups, consistent with findings by Melero et al. (2007).

Simultaneously, it can be seen that Figure 1. strong absorption bands around 1080–1000 cm^{-1} and 800 cm^{-1} were assigned to Si–O–Si stretching vibrations, indicating enhanced siloxane connectivity as calcination progressed. Notably, all lithium-modified samples exhibited new peaks between 850 and 950 cm^{-1}, assigned to Si–O–Li bond formation, confirming successful lithium anchoring within the silica network (Aman et al., 2019). A shoulder observed at 950–970 cm^{-1} also suggested interaction of lithium with terminal Si–OH groups, providing additional confirmation of surface functionalization. The observed FTIR results align closely with earlier reports on lithium-silica interactions and structural evolution during calcination.

The disappearance of silanol groups at higher calcination temperatures confirms thermal dehydration and condensation, as previously reported by Melero et al. (2007). Similarly, the shift in peak intensity in the 850–950 cm^{-1} range is consistent with Si–O–Li bond formation, as described by Aman et al. (2019). Furthermore, the strengthening of Si–O–Si networks observed at higher calcination temperatures supports the conclusions of Su and Guo (2014), who emphasized the role of thermal treatment in enhancing silica's structural stability. The progressive appearance of Si–O–Li peaks across calcined samples also correlates with enhanced basic site availability, echoing findings by Santos et al. (2011), who demonstrated that lithium incorporation increases basicity through the formation of these bonds. However, while previous studies have reported these phenomena in synthetic mesoporous silica systems,

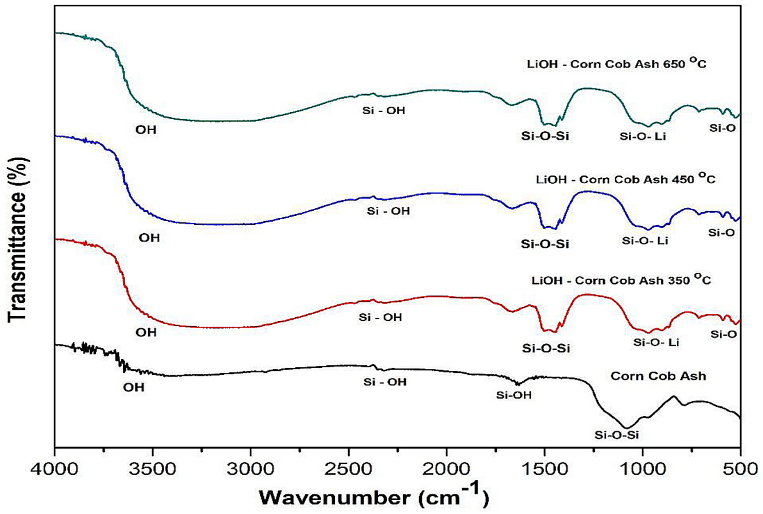

Figure 1. FTIR spectra

this study demonstrates similar outcomes using a sustainable biomass-derived precursor, offering environmental and economic advantages. This distinction underscores the novelty of the current approach. Studies by Haryono et al. (2023) and Shaikh et al. (2025) report similar band patterns, where Si–O–Si vibrations dominate the 1000–1100 cm^{-1} region, validating the presence of a silica backbone. Moreover, the emergence of Si–O–Li bands in the 1450–1500 cm^{-1} region has been reported as a hallmark of successful lithium incorporation in various silica-based catalysts. Shaikh et al. (2025) emphasized the role of these structural modifications in generating Lewis basic sites crucial for transesterification. Although their study involved titanium-based silica, the principle remains applicable, as lithium also induces local distortion and polar sites favorable for catalysis. However, unlike previous works where explicit FTIR shift-performance correlations were sparse, the present study establishes a direct structural evolution pattern tied to thermal treatment stages and lithium interaction.

Additionally, Karmee et al. (2025) note the lack of direct FTIR-based predictions of catalytic efficiency in lithium-based systems. In contrast, the present results suggest that Si–O–Li signal intensity and O–H band reduction could serve as reliable proxies for predicting catalyst activation and performance.

Scientifically, the FTIR analysis validates that lithium successfully binds to silica through Si–O–Li linkages, which increase the catalyst's structural robustness and basicity. The correlation between hydroxyl reduction and enhanced siloxane and lithium bond formation confirms the pathway for converting corn cob silica into a thermally stable, high-performance catalyst. Practically, the findings imply that controlled calcination can effectively tailor the surface chemistry of biomass-derived silica for catalytic applications. The enhanced Si–O–Si connectivity and Si–O–Li bonding improve resistance to leaching and elevate basic site density – both essential for high-yield transesterification. This positions lithium-modified corn cob ash as a viable, low-cost alternative to conventional catalysts in biodiesel production, aligning with circular economy and green chemistry principles.

XRD analysis

X-ray diffraction (XRD) analysis of corn cob ash and lithium-modified silica catalysts calcined at various temperatures demonstrated a clear transition in phase structure. From Figure 2. The raw corn cob ash exhibited a broad halo centered around $2\theta \approx 22°$, indicating the presence of largely amorphous silica. Upon lithium impregnation and calcination at increasing temperatures (350 °C, 450 °C, and 650 °C), distinct diffraction peaks began to emerge, particularly in the regions between 30–35° and 40–50° 2θ. These are characteristic of crystalline lithium silicate phases, including lithium metasilicate (Li_2SiO_3) and lithium tetrasilicate (Li_4SiO_4), confirming successful structural transformation (Kulkarni et al., 2006; Xie et al., 2011).

The intensity and sharpness of these peaks increased progressively with calcination

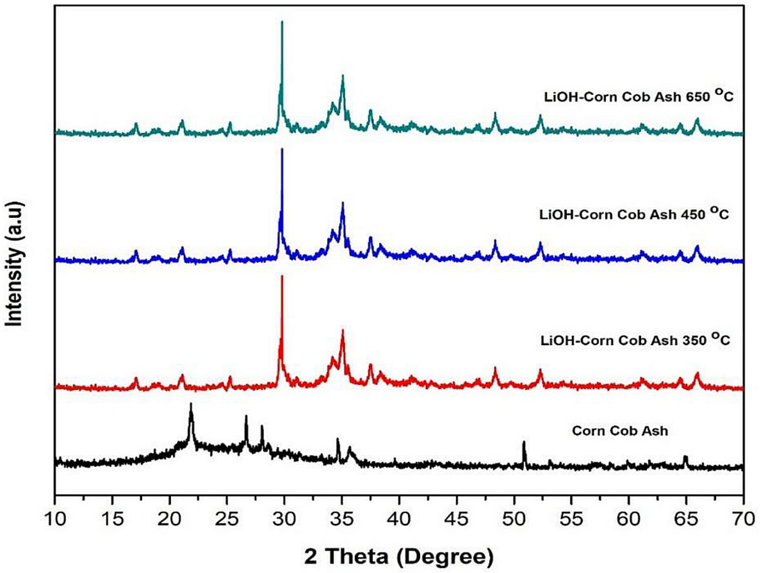

Figure 2. XRD patterns

temperature, indicating enhanced crystallinity. However, the presence of an underlying broad halo in all samples implies that the catalyst matrix retained a mixed amorphous-crystalline structure across all calcination conditions. This hybrid structural feature is beneficial for catalytic applications, offering both high surface area and defined reactive sites.

The findings are consistent with literature reporting the formation of Li_2SiO_3 and Li_4SiO_4 under moderate to high calcination temperatures (Kulkarni et al., 2006; Su and Guo, 2014). The appearance of these crystalline phases at temperatures as low as 350 °C aligns with earlier observations on lithium silicate formation but is particularly significant here due to the biomass-derived nature of the silica. Xie et al. (2011) identified Li_4SiO_4 as a phase that enhances catalyst basicity, and its presence in the 450 °C and 650 °C samples reinforce the expected performance improvements. Furthermore, the preservation of an amorphous component across all samples is supported by Majedi and Safaei (2023), who emphasized the reactivity of amorphous silica due to its extensive surface area and flexible structure. While previous studies have focused on synthetic or mineral silica sources, this study uniquely demonstrates that corn cob ash, an agricultural waste, can also yield a similarly beneficial phase composition. This supports Vicente et al. (2010), who noted that mixed-phase catalysts exhibit superior transesterification performance. The formation of crystalline lithium silicates such as Li_2SiO_3 and Li_4SiO_4 in lithium-modified silica systems (Haryono et al., 2023; Shaikh et al., 2025). As established in prior studies, Li_2SiO_3 tends to form at lower temperatures, while Li_4SiO_4 formation becomes significant above 600 °C. The present study reflects this trend, with increasing calcination temperature from 350 °C to 650 °C driving the evolution of more intense and sharper crystalline peaks associated with these lithium silicates. Shaikh et al. (2025) emphasized that the emergence of these crystalline phases correlates strongly with enhanced catalyst basicity, which is essential for transesterification. Moreover, Balasubramanian et al. (2025) linked these phase transformations to improvements in methyl ester yield. In alignment with these studies, the current XRD results substantiate that higher crystallinity and lithium silicate phase purity, especially at 650 °C, are likely contributing factors to increased biodiesel yield observed in the catalytic tests. Distinct from studies focusing solely on crystalline systems, this work highlights the coexistence of amorphous and crystalline phases, offering a structural balance. Such a combination may impart additional benefits, including higher surface area from amorphous domains and catalytic strength from crystalline domains, a synergy not extensively explored in existing literature.

Scientifically, the XRD analysis confirms that lithium-modified corn cob silica catalysts undergo a structured transformation that enhances their crystallinity and catalytic potential. The formation of lithium silicates such as Li_2SiO_3 and Li_4SiO_4, along with retention of amorphous regions, produces a structurally balanced catalyst. This hybrid structure provides an optimal combination of high surface area, basicity, and thermal stability. Practically, these findings indicate that calcination at around 650 °C is sufficient to produce a stable and active catalyst without compromising porosity. Maintaining crystallinity within a controlled threshold avoids pore collapse, a problem observed at excessively high temperatures (>800 °C) (Babaki et al., 2016; Carrero et al., 2017). Thus, lithium-impregnated corn cob silica catalysts present a cost-effective and scalable option for biodiesel production, contributing to both catalytic efficiency and the broader objectives of waste valorization and circular economy integration.

SEM EDS analysis

SEM imaging revealed a substantial morphological transformation between raw corn cob ash and lithium-impregnated samples subjected to calcination. The untreated corn cob ash exhibited a porous, fibrous architecture with visible microchannels, ideal for high surface area applications. Figure 3 show upon lithium incorporation and thermal treatment at 450 °C, 550 °C, and 650 °C, the surface morphology transitioned into rough, flake-like agglomerates. This transformation reflects the deposition of lithium species and partial sintering effects, particularly at elevated temperatures.

Form Table 1. EDS analysis showed that Li_2O content increased significantly with calcination: from 0.95% in raw ash to 15.75% at 450 °C, peaking at 17.90% at 550 °C before declining slightly to 16.50% at 650 °C. Conversely, SiO_2 content decreased from 76.75% to 65.70–67.75%, indicating partial replacement of silica by lithium compounds. Minor metal oxides (K_2O, Na_2O, MgO, CaO) diminished post-acid leaching, highlighting purification efficiency. The elemental profile confirms a favorable balance of basic metal oxides supporting active site formation.

The morphological shift from fibrous to flake-like structures is consistent with observations by Xie et al. (2015), who reported that lithium incorporation alters silica texture due to sintering and structural densification. At moderate calcination temperatures (450–550 °C), lithium dispersed well, retaining high surface area and porosity. Baingam et al. (2025) emphasized the benefit of preserving amorphous character to maintain pore accessibility, a condition maintained up to 550 °C in this study. At 650 °C, partial pore collapse began to emerge, aligning with findings by Doyle et al. (2016), who noted reduced textural properties at excessive calcination temperatures. Regarding elemental loading, Marwan (2016) and Serio et al. (2007) identified 5–15% Li_2O as optimal for biodiesel catalysis. The current study's 17.90% peak at 550 °C slightly exceeds this range but still delivered superior morphology and phase development, confirming it as the thermal optimum. The decrease in minor oxides following acid leaching matches earlier results by Melero et al. (2008) and Chuayplod and Trakarnpruk (2009), affirming improved silica purity. Furthermore, the synergistic influence of SiO_2, Li_2O, K_2O, and MgO observed here aligns with Santos et al. (2011), supporting a multicomponent strategy for maximizing basic active site availability.

These observations align well with prior studies describing morphological and compositional transformations in lithium-modified silica catalysts. Haryono et al. (2023) reported that lithium integration enhances surface area and induces porosity modifications due to the formation of lithium silicate phases. However, in this study, SEM images suggest a densification trend instead of surface expansion, which may be attributed to excessive lithium loading and partial collapse of microstructure during thermal treatment, a variation not emphasized in earlier literature.

Balasubramanian et al. (2025) documented particle size reduction and improved surface dispersion due to lithium impregnation. While the current findings indicate major surface roughening and flake formation, direct evidence of nanoscale particle reduction is less conclusive. However, the increase in lithium content and decrease in impurities support the conclusion that lithium played a dominant role in modifying structural features.

In terms of EDS findings, the data concur with literature reports emphasizing the relationship between lithium loading, catalytic stability, and impurity elimination (Shaikh et al., 2025; Karmee et al., 2025). The high Li_2O levels achieved at 550 °C in this study are among the highest reported for biomass-derived silica catalysts, indicating an optimal thermal window for maximum lithium incorporation. These values also highlight a potential upper limit for lithium loading, as a slight decline in Li content was observed at 650 °C, possibly due to surface sintering or phase volatilization

Table 1. Elemental analysis

No	Sample	SiO_2 (%)	K_2O (%)	Na_2O (%)	Li_2O (%)	MgO (%)	CaO (%)	Others (%)
1	Corn cob ash	76.75	7.15	1.50	0.95	2.54	3.75	7.36
2	LiOH-Corn cob ash 450 °C	65.70	8.20	1.20	15.75	0.37	0.40	8.38
3	LiOH-Corn cob ash 550 °C	67.75	8.50	1.45	17.90	0.45	0.50	3.45
4	LiOH-Corn cob ash 650 °C	66.25	8.25	1.30	16.50	0.42	0.43	6.85

Scientifically, the data validate that lithium incorporation induces significant morphological restructuring while enhancing basic oxide content. This transformation enhances the catalytic active surface and promotes robust Si–O–Li bond formation, particularly effective at 550 °C. The retention of a partially amorphous framework ensures sufficient surface area and pore volume for mass transport during transesterification. Practically, these findings support the selection of 550 °C as the optimal calcination temperature for maximizing catalytic performance while avoiding excessive lithium aggregation or structural collapse. The combination of high Li_2O content and minimized impurities results in a structurally and compositionally optimized catalyst. These insights guide scalable, waste-derived catalyst production for efficient biodiesel synthesis, reinforcing sustainability and circular economy goals.

Fatty acid analysis

Gas chromatography–mass spectrometry (GC–MS) analysis of the refined, bleached, and deodorized palm oil (RBDPO) feedstock revealed a predominance of monounsaturated and saturated fatty acids. From Table 2. Oleic acid (C18:1) was the major component at 47.56%, followed by palmitic acid (C16:0) at 36.60%, and linoleic acid (C18:2) at 11.96%. Minor components (<2%) included lauric, myristic, stearic, palmitoleic, linolenic, arachidic, and eicosenoic acids.

The average molecular weight of the triglycerides was determined to be 848.6022 g/mol. The feedstock had a free fatty acid (FFA) content of 0.15% and a moisture content of 0.07%, both well within the optimal range for base-catalyzed transesterification. These physicochemical characteristics confirm the high suitability of RBDPO for efficient biodiesel production using basic heterogeneous catalysts.

The fatty acid profile from Table 2. is consistent with reported compositions of RBDPO, which commonly feature high proportions of oleic and palmitic acids (Chuayplod and Trakarnpruk, 2009). The high oleic acid content supports efficient transesterification due to greater molecular flexibility and accessibility to catalytic sites, aligning with studies that highlight enhanced reactivity of unsaturated fatty acids (Melero et al., 2008). The FFA level of 0.15% is significantly below the 1.5 wt% threshold commonly cited in the literature for heterogeneous base-catalyzed reactions (Serio et al., 2007). This ensures minimal soap formation, thereby maximizing biodiesel yield and simplifying downstream purification. The low

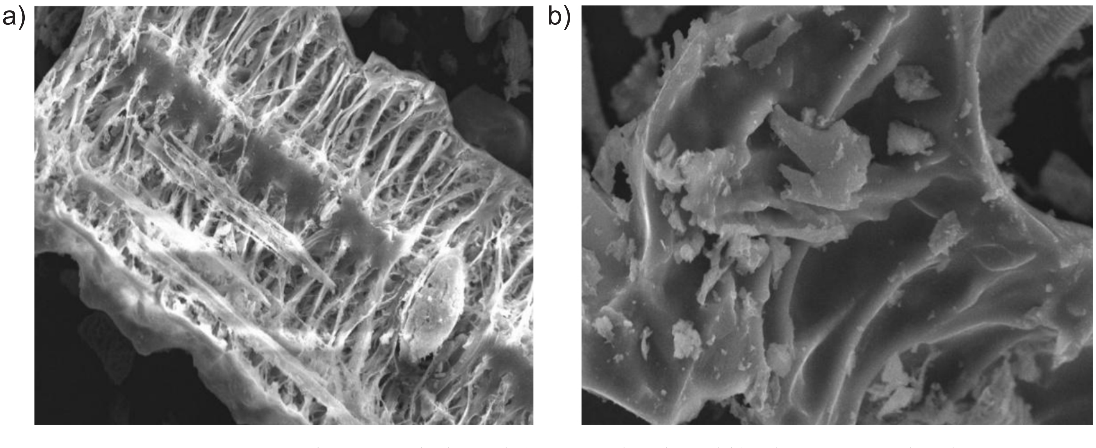

Figure 3. Surface morpholgy of a) corn cob ash and b) LiOH-corn cob ash

Table 2. Component of fatty acid

Peak number	Retention time (minutes)	Component	% (b/b)
1	2.919	Lauric acid (C12:0)	0.31
2	3.570	Myristic acid (C14:0)	1.01
3	4.814	Palmitic acid (C16:0)	36.60
4	5.105	Palmitoleic acid (C16:1)	0.11
5	6.450	Stearic acid (C18:0)	1.86
6	6.750	Oleic acid (C18:1)	47.56
7	7.168	Linoleic acid (C18:2)	11.96
8	7.762	Linolenic acid (C18:3)	0.19
9	8.183	Arachidic acid (C20:0)	0.21
10	8.516	Eicosenoic acid (C20:1)	0.13

moisture content (0.07%) is also consistent with the acceptable upper limit of 0.1 wt% for maintaining high catalytic efficiency. Excess moisture is known to trigger hydrolysis of triglycerides, increasing FFA and reducing yield, as noted by Marwan (2016). In this case, the feedstock's moisture content poses no risk to catalyst performance. Regarding molecular weight, the triglyceride average of 848.6022 g/mol implies the need for an elevated methanol-to-oil molar ratio, supporting the use of a 12:1 ratio in the present study. Literature (Vicente et al., 2010) affirms that higher molecular weights correlate with slower kinetics and increased methanol demand to maintain reaction efficiency.

The compositional profile of RBD palm oil observed in this study aligns with the general fatty acid distribution of palm oil reported by Haryono et al. (2023), which highlights a typical range of approximately 41% saturated, 45% monounsaturated, and 14% polyunsaturated fatty acids. The identified levels of palmitic and oleic acids in our analysis are consistent with these benchmarks, reinforcing the reliability of palm oil as a biodiesel feedstock. The linoleic acid content (11.96%) also matches reported norms for palm oil, distinguishing it from alternatives like soybean oil, which is richer in polyunsaturated fatty acids (~50% linoleic acid). Additionally, the low FFA content in the present RBD palm oil (0.15%) underscores its superior suitability compared to feedstocks such as Jatropha or tallow, which frequently exhibit elevated FFA levels necessitating pretreatment (Shaikh et al., 2025).

Moisture content in the studied sample (0.07%) was notably lower than levels commonly found in used cooking oils or animal fats, where water content often leads to hydrolysis and reduced transesterification efficiency. This concurs with observations by Shaikh et al. (2025), who noted the importance of moisture control to mitigate saponification and maintain biodiesel yields. The calculated triglyceride molecular weight (848.6022 g/mol) falls within expected ranges, facilitating precise methyl ester conversions. These combined attributes highlight the consistent performance and reliability of RBD palm oil relative to other biodiesel feedstocks.

Scientifically, the analysis confirms that RBDPO is an ideal candidate for base-catalyzed transesterification, with its favorable fatty acid profile, low FFA and moisture levels, and well-characterized triglyceride molecular weight. These properties ensure minimal side reactions and high conversion rates under optimized conditions. Practically, the feedstock characteristics reduce the need for pre-treatment steps such as acid esterification, streamlining the biodiesel production process. The high proportion of unsaturated fatty acids like oleic acid enhances reactivity, while the acceptable FFA and moisture levels ensure compatibility with lithium-modified silica catalysts. This supports the feasibility of integrating such feedstocks into scalable, low-impact biodiesel production systems using heterogeneous base catalysts.

Biodiesel yield and catalytic performance

Catalytic performance evaluation of lithium-impregnated corn cob silica across different calcination temperatures showed biodiesel yields of 80%, 85%, and 82% at 450 °C, 550 °C, and 650 °C, respectively. Figure 4 showed The highest yield was recorded at 550 °C, corresponding to optimal lithium oxide (Li_2O) content and the formation of active lithium silicate phases.

From Figure 4, at 450 °C, the catalyst exhibited sufficient reactivity, though incomplete crystalline phase development and lower Li_2O availability limited its full potential. At 650 °C, partial sintering and decreased porosity likely hindered reactant diffusion, reducing active site accessibility and thus yield. In contrast, the 550 °C condition achieved a balance between crystalline lithium silicate phase formation and preservation of the amorphous structure, enabling superior surface area and catalytic efficiency.

These yield patterns are consistent with established studies on lithium-modified catalysts.

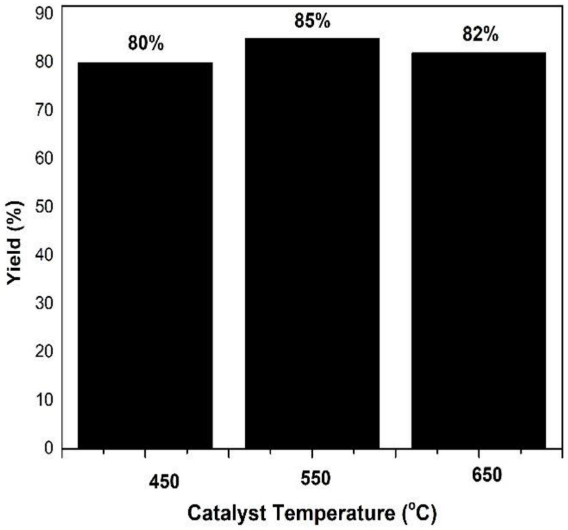

Figure 4. Effect of calcination temperature on biodiesel yield

Maseko et al. (2025) affirmed that high surface area and lithium silicate phases promote increased catalytic basicity and reactivity, especially when formed under optimal thermal conditions. The 550 °C catalyst fits this profile by achieving high Li_2O content while avoiding structural collapse, confirming the correlation between lithium incorporation and biodiesel productivity. Porosity preservation was critical, as reported by Melero et al. (2008), who emphasized the role of silica's porous framework in facilitating mass transfer and reactant accessibility. The slight performance drop at 650 °C aligns with Zeng et al. (2020), who observed that sintering at elevated temperatures reduces pore volume, diminishing catalyst efficiency. Furthermore, Wang et al. (2015) highlighted that lithium oxide content within the 5–15 wt% range maximizes catalytic yield by forming stable lithium silicates such as Li_2SiO_3 without over-saturating the catalyst surface. Excessive Li_2O or crystallinity, as observed at 650 °C, can block active sites, reduce reactivity, and impair diffusion pathways, corroborating the slightly lower yield in this condition.

The observed maximum yield of 85% at 550 °C lies within the reported performance range for lithium-based heterogeneous catalysts, which spans from 70% to over 90% under optimized conditions (Haryono et al., 2023). This yield level affirms the catalyst's effective performance when calcination parameters are precisely controlled. Compared to other findings where peak yields exceed 90%, the slightly lower yield in this study may be influenced by specific feedstock properties or marginal variations in catalyst formulation. The degradation in yield at 650 °C aligns with previous studies emphasizing that over-calcination may cause sintering, leading to diminished active surface area and reduced catalytic efficiency (Shaikh et al., 2025).

Furthermore, literature has underscored the role of Li_2O concentration in enhancing catalyst performance. The 17.90% Li_2O content observed here supports the assertion that lithium-rich surfaces promote transesterification. However, excessive thermal treatment beyond optimal temperature compromises this benefit, reinforcing the need for precise thermal control. These comparative insights emphasize the consistency of the present findings with established research while also highlighting critical thresholds for maintaining catalytic activity.

Scientifically, the findings reinforce that 550 °C is the optimal calcination temperature for lithium-impregnated biomass-derived silica catalysts. This condition promotes phase formation (Li_2SiO_3), enhanced basicity, and stable structure without compromising porosity, enabling efficient transesterification. From a practical perspective, maintaining calcination around this thermal window allows scalable production of efficient catalysts from agricultural waste, such as corn cob ash. This aligns with the principles of green chemistry and circular economy, enabling high-yield biodiesel synthesis while minimizing environmental impact and material costs. These results also inform future catalyst design strategies where phase formation, surface area retention, and optimal lithium loading must be precisely controlled to ensure maximum catalytic performance.

CONCLUSIONS

This study successfully demonstrates the development of a structurally optimized lithium-impregnated silica catalyst derived from corn cob waste. The catalyst calcined at 550 °C achieved a biodiesel yield of 85%, outperforming other calcination temperatures due to the formation of stable lithium silicate phases (Li_2SiO_3 and Li_4SiO_4), high Li_2O content (17.90%), and preserved porosity. Characterization results confirmed the formation of Si–O–Li bonds and mixed amorphous-crystalline morphology, essential for maintaining basicity and catalytic performance under transesterification conditions. The RBDPO feedstock, with low FFA and moisture, complemented the base catalyst, allowing for efficient conversion without pre-treatment. Compared to conventional catalysts, the lithium-modified corn cob silica catalyst offers better thermal stability, lower leaching, and ease of recovery, aligning with sustainable production goals. This research advances the application of circular economy principles in biodiesel catalysis, providing a scalable and eco-friendly alternative for converting agricultural waste into high-efficiency catalysts. Further studies could explore catalyst regeneration and performance under continuous operation to evaluate industrial viability.

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