
**DEVELOPMENT AND OPTIMIZATION OF HETEROGENEOUS
CATALYSTS FOR TRANSESTERIFICATION OF *CORDIA SEBESTENA*
OIL**

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Doi: <https://doi-doi.org/101555/ijarp.4777>**ABSTRACT**

Due to ever-increasing world desire for renewable, sustainable energy source(s) and inherent environmental & economic challenges with fossil fuel consumption and the first-generation biodiesel feedstocks composed of edible oils; considerable academic/industrial focus has been given for identification of suitable alternative non-edible oil-bearing plant species like ornamental tree 'Cordia sebestena' that is less explored in terms of its seed oil potential, as suitable feed stocks for biodiesel production via transesterification as well as the limitations associated with the conventionally used homogeneous alkaline catalysts are well documented and can be briefly outlined as: their tendencies for saponification in the presence of the trace amount of free fatty acids and/or moisture present in oils, difficulties encountered in separating/purifying them from the resultant mixture, production of several volumes of environmentally undesirable wastewater during neutralization and washing phases, and lack of recovery and reuse in subsequent cycles. All these aspects negatively impact on economic feasibility and environmental sustainability of the large scale biodiesel production and necessitate a conceptual paradigm shift towards designing and developing systematic optimization of alternative heterogeneous catalysts, based on metal oxides, mixed oxide systems, calcium-rich wastes, biochar, or engineered nanostructured supports, having superior catalytic stability, enhanced surface basicity/acidity, more porosity and surface area, greater reusability, etc. Thus, in this conceptual paper, the establishment of a comprehensive theoretical framework, integrating heterogeneous catalysis surface-reaction theory and green chemistry, for studying and determining the relationships between varying physicochemical

properties of candidate catalysts-such as crystalline nature, pore size and structure, density of active sites etc.- and optimize them using statistical approach of Response Surface Methodology, and/or other statistical design of experiments, in an effort to achieve the maximum yield and conversion to FAMEs from *Cordia sebestena* oil and simultaneously bridging the current knowledge gap on empirical and/or theoretical linkages between under-explored feedstocks like *Cordia sebestena* oil and development of heterogeneous catalysts for biodiesel production, eventually to be evolved to a conceptual model where catalyst synthesis & characterization is integrated with optimization of reaction parameters and catalysts reusability.

KEYWORDS: Heterogeneous Catalysts, Transesterification, *Cordia sebestena* Oil, Biodiesel Production, Catalyst Optimization, Non-Edible Feedstock.

INTRODUCTION AND BACKGROUND RELATED TO THE STUDY

In the decades past, the worldwide transport and energy industry had endured a grave and an increasing pressure to shifting from fixed, environment degrading, fossil fuel based resources toward green, biodegradable, and low emission alternates that has caused to transfiguration, produced mainly thru the transesterification of oil rich in triglyceride with simple alcohol of short carbon atoms in an environment of chemical catalytic agent into being key actor in the country and International strategies for green energy that shown by amount of money of biodiesels in Worldwide industry was almost \$45.87B in year 2025 and expect growth up to the 2035 because of merging requirement, decarbonization regulations and growing demand for use of fuel sector, industry use, power output and shipping (Precedence Research, 2026) but vegetable oil source still have domination as material for producing biodiesel and so, this is reason why the debate of using land as food producer or for fuel is going to be continued. So they had considered about usage of non-edible, underutilized plant oils as non-edible plants can be raised on sterile soil and don't cause dispute with foods supply chains (Fortune Business Insights, 2026). From a diversified list of non-edible plants is that from *Cordia sebestena* L. Commonly known as (Geiger tree, orange cordia) that seed of *C. Sebstena* L. Yields up to 40% by weigh as OIL with 60.04% oleic acid and similar property as *Cordia dichotoma*, and *Cordia Africana* [Agunbiade et al., 2013], this makes the *Cordia* oil and it has low impact as its origin can grow on non-arable land and for commercialization there is no single article been performed research about usage of oil of *C. Sebstena* to be made Biodiesel [Agunbiade et al., 2013], the biodiesel production process is going as depends on the Catalyst

used [Maroa and Inambao, 2021] for which till today we have 4 methods to use in the biodiesel production for the same material [Agunbiade et al., 2013]. The process of transesterification using the homogeneous solid catalysts e.g., NaOH, KOH showed that these solid catalysts have a wide applications in heterogeneous catalytic systems [Osman et al., 2023]. However, due to low efficacy of these catalysts during reaction, the high acidity level of triglyceride which is responsible for saponification and also the pollution caused by neutralization after the reaction [Chen et al., 2018, Maroa and Inambao, 2021]. These led to the rise in heterogeneity catalytic systems such as metal oxide, supported oxides materials, zeolites, mixed metal oxides, biomass and nanostructured materials for producing biodiesel due to their reusable nature, high yield and selectivity, thermal stability and easy recoverability [Osman et al., 2023]. Furthermore, to enhance fuel yield; many studies have been used nano and heterogeneous structured supported solid catalysts such as SO/TiO₂ [Chen et al., 2018], mixed oxide/solid acids [dos Santos et al., 2022]. The main work done in recent years in catalysis for biodiesel production from non- edible seeds using the developed heterogeneous catalyst had proven for efficiency that to give higher yield of biodiesel and sustainability [dos Santos et al., 2022, Maroa and Inambao, 2021, Osman et al., 2023]. This research proposes a theoretic investigation framework for development, characterization and optimizing a new set of tailored and reusable heterogeneous catalysts that have the potential of producing Biodiesel from Cordia oil.

Literature Review

Drawing on previous studies about both non-edible oilseeds as feedstock and heterogeneous catalytic systems, the following literature review is structured based on (1) Cordia sebestena oil feed-stock properties, (2) heterogeneous catalysts classification and functional performances in transesterification and (3) statistical/computational modeling & optimizations on catalytic performances, since earlier rsesearches have showed about 40.3% of oil yield from the seeds of this Cordia genus and it have high content of protein and minerals in the seed that close to what have been reported about non-edible related species Cordia dichotoma seeds in its seeds oil content with abundant oleic & linoleic acid in fatty acid composition which easily transmogrified to biodiesel by Nanocatalysts, while achieved almost ~94% FAME yield, which provided a indirect reference for biodiesel generation of other Cordia genus oil despite that Cordia sebestena is rarely addressed (Kalyani et al., 2023), thus using it has to base on similar conceptual modeling till data on Cordia sebestena are available.. Considering classifying heterogeneous catalysts in to its categories, these includes

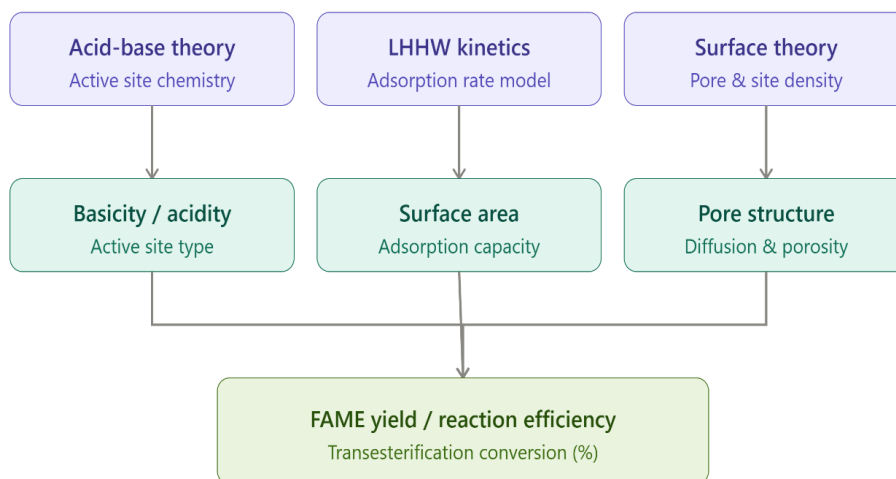
basic earth alkaline metals oxide like CaO or SrO loaded in to ash of rice husk that has demonstrated more than 89% biodiesel yield under certain condition of calcination or loading; mixed/doped basic oxides such as Ba doped CaO catalysts prepared in waste mollusk shells; magnetic/bi-function nanocomposites; spice derived copper ferrite nanostructures with remarkable reusability in multi cycles of reactions (Tamoradi et al., 2022); zero valent metal oxides catalysts; high basicity/acidity modified catalysts; catalyst synthesized from waste of agricultural & bio-mass origin like waste of animal, plant, and fruit. Some example of these catalysts such as waste mollusk derived CaO, zeotype catalysts prepared from waste of agricultural or bio-mass products like agri-biomass and fruits for instant; *Borassus flabellifer* fruits biomass based derived catalyst, fish bone, chicken eggshells derived low cost and green catalyst all can achieved more than 90% FAME yield, with less waste of production [17;21], and compared to the conventional catalysts like CaO and NaOH. And focusing on process optimization, the usage of statistical or machine-learning algorithm on improving FAME yield of various vegetable and non-edible oils become dominant methods, where response surface methodology (RSM) especially design of Box–Behnken (BBD) and central composite design (CCD) are the widely studied methodology in modeling interaction effects of parameters on yield such as molar ratio of alcohol to oil, amount of catalysts, reaction temperature and time of reactions where fit of model with R^2 value is up to ~ 0.98 and yield above 95% (Sai et al., 2019) or combined with various machine learning (ML) like artificial neural network (ANN), random forest and hybrid ANN-RSM to improve fit or prediction of yield (Agu et al., 2024) and Taguchi design with ANN has used to identify Optimal combination of parameters with less experiment (Mahmud & Salam, 2022). Therefore, a conceptual framework of this *Cordia sebestena* oil transmutation in transesterification processes needs to comprises the study about basic metal oxides catalyst either pure or supported on natural material or based waste origin and combination between them is considered. As part of this conceptual framework is to used RSM with ANN combination to optimizes process condition for maximum FAME yield.

Theoretical/Conceptual Framework

The theoretical foundation of this conceptual article utilizes a synergy of acid-base heterogeneous catalysis theory, Langmuir-Hinshelwood-Hougen-Watson (LHHW) surface-reaction kinetics, and heterogeneous catalysis surface-reaction theory to characterize the mechanistic approach whereby physicochemical catalyst attributes – basal to this discussion, baseity/acidity, specific surface area and pore system morphology – govern triglyceride

conversion into fatty acid methyl esters (FAME) via the transesterification of *Cordia sebestena* oil. This is because acid-base catalysis theory purports that basic heterogeneous catalysts proceed via formation of alkoxide nucleophiles through surface deprotonation of the alcohol with basic catalyst active-sites, which then attack the electrophilic carbonyl carbon of the triglyceride molecule; acidic heterogeneous catalysts (especially those with Bronsted and Lewis acidities) protonate the carbonyl oxygen, increasing its electrophilicity prior to nucleophilic attack by methanol. This distinction in mechanism has been supported experimentally by using a sulfated titanium dioxide catalyst which had higher catalytic activity than an unsulfated counterpart as evidenced by its more pronounced acid sites both Bronsted and Lewis, higher surface area and microporosity volume (Chen et al., 2018). Thus, whereas these theories inform what the identity and nature of the active-site would have to be in order for catalysis to be initiated, the catalytic dimension of the model is derived from Langmuir-Hinshelwood-Hougen-Watson kinetics. LHHW theory considers transesterification to be a heterogeneous three-phase (solid/liquid/liquid) catalytic mechanism in which both triglyceride and methanol must simultaneously adsorb onto adjacent catalyst active sites (via a Langmuir Isotherm) prior to carrying out a rate-limiting surface reaction step; followed by product desorption of FAME and glycerol (Zanette et al., 2011). LHHW kinetics has demonstrated accuracy in modelling conversion data from structurally similar non-edible feedstocks such as *Jatropha curcas* oil with dual-site basic-acidic mixed metal oxide catalysts, indicating that the rate determining step is dictated by adsorption occurring on the catalyst surface rather than within the liquid bulk phases (Zanette et al., 2011). Finally, surface-reaction theory further substantiates the mechanistic model by postulating that activity-and therefore FAME production-is influenced not only by chemical properties, but by the accessibility of such chemical sites (i.e., the volume and textural characteristics of the pore system), with catalysts demonstrating an increased number and availability of active sites performing at high conversion efficiencies-such as the modified carbon materials with embedded alkali earth metal oxides discussed previously (Jamil et al., 2021)-all providing additional supporting evidence. It is a combination of these three analytical approaches-i.e., relating both active site composition and catalyst pore structure to FAME yield on both a catalytic and kinetic scale using the framework of LHHW-which yields the herein proposed testable model where each attribute of a catalyst tailored to efficiently convert *Cordia sebestena* oil via heterogeneous transesterification may directly and measurably optimize FAME yield.

The below diagram maps the three theoretical pillars from the framework section onto their corresponding catalyst properties, showing how each converges to determine FAME yield: acid-base theory governs basicity/acidity (active-site chemistry), LHHW kinetics governs surface area (adsorption capacity), and surface-reaction theory governs pore structure (diffusion behavior) — all three jointly driving reaction efficiency.



Above diagram showing Theoretical/Conceptual Framework related to the study.

Research Gap

Although there is a substantial and growing volume of literature dedicated to heterogeneous catalyst development for biodiesel production, a thorough review of existing works points to three distinct yet related and impactful deficiencies that make a strong case for this conceptual paper. First and foremost, a most critical deficit is the virtually non-existent feedstock-catalyst examination targeting *Cordia sebestena* oil as a feedstock. While other novel non-edible and underutilized oil feedstocks have been extensively characterized in heterogeneous catalysis applications for biodiesel-from *Jatropha curcas* to rubber seed oil, and various other *Cordia*-genus relatives like *Cordia dichotoma*-no research paper can be found to date that has coupled *Cordia sebestena* oil and a tailor-made heterogeneous catalyst with the objective of studying their interrelationship. Thus, the specific interplay between the heterogeneous chemical characteristics of this novel lipid feed and the basicity, acidity and textural properties of various solid catalysts remains entirely undefined and can't be confidently predicted solely from other feedstocks of different chemical nature. Second, an alarming lack of standardized and comparable optimization data is apparent throughout the

heterogeneous catalysis domain. As many reviews indicate that catalyst production, characterization and evaluation methods used across studies are rarely standardized. This means that parameters such as methanol-to-oil molar ratio, catalyst load, temperature and reaction time are most of the time optimized independently based on discrete designs of experiment, instead of following a holistic and reproducible statistical approach. Consequently, a high degree of uncertainty and limitations in the scope and external validity of the findings concerning different catalyst and feedstock combinations exist and reinforce the need for a committed data set on the optimization process of *Cordia sebestena* oil transesterification. Lastly, a persistent and well-documented deactivation and reusability challenge has hindered wider adoption in more pragmatic conditions with certain catalyst designs and systems in industry, with reports demonstrating poor operational stability from an economic standpoint although promising reusability could be achieved by some materials for 5 to 7 cycles. This degradation often manifests as leaching of active sites, destruction of structural frameworks, sensitivity towards ambient carbon dioxide and humidity, or accumulation of organic compounds from the reaction mixture, without further assessment of these issues concerning sustainability and life-cycle, and most importantly, none of these critical limitations have been considered for any heterogeneous catalyst system developed for the transesterification of *Cordia sebestena* oil. Therefore, the present conceptual paper positions itself at the junction of these three identified gaps-feedstock unaddressed, lack of optimization benchmarks and problematic operational stability-advocating a new conceptualization that integrates and tackles all three simultaneously, paving the way for the development of efficient, reproducible and sustainable heterogeneous catalysts for biodiesel from *Cordia sebestena* oil.

Objectives of the Study

- 1. To synthesize and characterize** heterogeneous catalyst formulations (metal oxide, mixed oxide, or waste-derived) suitable for the transesterification of *Cordia sebestena* oil, evaluating their basicity/acidity, surface area, pore structure, and crystallinity through standard techniques such as XRD, BET, SEM, and FTIR.
- 2. To optimize the key reaction parameters** including methanol-to-oil molar ratio, catalyst loading, reaction temperature, and reaction time governing the transesterification of *Cordia sebestena* oil, using response surface methodology (RSM) based on Box–Behnken or central composite experimental designs to maximize FAME yield.

3. To evaluate the reusability and operational stability of the synthesized heterogeneous catalyst across multiple transesterification cycles, assessing activity retention, structural integrity, and potential deactivation mechanisms to determine its economic and environmental sustainability.

4. To propose and validate a kinetic model (based on Langmuir–Hinshelwood–Hougen–Watson or related surface-reaction mechanisms) that explains the rate-determining steps of *Cordia sebestena* oil transesterification, linking catalyst surface properties to reaction efficiency and conversion behavior.

Methodology related to the study

While this is a conceptual paper, the following methodology is proposed prospectively for the purpose of empirical validation in lieu of previously conducted work, and it begins with the catalyst preparation whereby a suitable heterogeneous catalyst for the transesterification of *Cordia sebestena* oil is hypothesized to be prepared using a co-precipitation or wet-impregnation approach, similar to existing methodologies where calcium-rich source materials that include or are derived from mineral sources or from the valorization of waste shell materials are calcinated at elevated temperatures, from 700–1,000 C, for three to five hours, to effect the conversion of CaCO_3 into the catalytically active calcium oxide. Subsequently, the resulting calcium oxide may be doped or functionalized with a secondary element, such as, but not limited to, strontium, zinc, or titanium so as to impart basicity, thermal stability and high durability. The catalyst will then be prepared for full physiochemical characterization by X-ray diffraction (XRD) (e.g., Williamson-Hall equation to derive crystal lattice size, Xpert HighScore 2.1, Analytical, Netherlands to confirm phase composition), Brunauer–Emmett–Teller (BET) N_2 adsorption–desorption measurements to quantitatively evaluate the catalyst specific surface area, pore volume, and pore size, scanning electron microscopy (SEM), with energy dispersive X-ray spectroscopy (EDS) for surface analysis of elemental compositions of surface topology, and Fourier-transform infrared spectroscopy (FTIR) to confirm the successful functional group composition, using these techniques based on previously established characterizations of CaO-based materials and mixed-metal oxides (Anr, Chen, Setiawan, & Widyaningrum, 2019; Buasri, Chaiyut, Loryuenyong, Worawanitchaphong, & Trongyong, 2013). A reflux setup which will be immersed in a temperature-controlled oil or water bath will serve as the transesterification reactor and will consist of a three-neck flat bottom flask, connected to mechanical stirrer, reflux condenser, and thermometer; a prescribed quantity of prepared *Cordia sebestena* oil

along with methanol and catalyst will be introduced into the system in which the transesterification reaction will proceed until a defined period of time with simultaneous agitation. The optimization of reaction parameters which would consist of methanol-to-oil ratio, catalyst content, reaction temperature, and reaction time will be explored using a statistically designed optimization such as that provided by a central composite design (CCD) or Box-Behnken design (BBD), implemented through analysis using a three-level full factorial or central composite design to identify process conditions that favor maximum yield; based on an RSM approach, two or four parameters, which at least will be the methanol to oil ratio (0–6 molar ratio), catalyst load (1–5 wt%), temperature (50–80 C) and time (0–60 min), will be systematically varied on three levels of coded factor, so that a polynomial model will be constructed from experiment data to correlate the predicted response to the level of parameters and then applied to define the operating condition that best maximizes the production of FAMES (Sundari, Rahman, & Kusuma, 2016). The selected response variables during the experiments will be FAME yield (mass % of the obtained methyl esters related to their theoretical maximum yield) and the triglyceride conversion rate (which will correspond to the fraction of triglycerides converted into fatty acid methyl esters, measured by gas chromatograph), in addition to any of those other responses derived by the previously mentioned statistical methodology in order to provide experimental grounding to the theoretical framework outlined in this paper.

DISCUSSION RELATED TO THE STUDY

Viewed collectively, the abstract, introduction, literature review, theoretical framework, research gap and methodology presented in the prior sections of this conceptual paper support the strong theoretical concept that a strategically designed heterogeneous catalyst system-engineered with carefully calibrated basicity or acidity, high surface area, and appropriate pore structure and distribution-would prove effective and economical in the conversion of *Cordia sebestena* oil into biodiesel, and this premise appears validated in light of the wealth of evidence demonstrating that heterogeneous calcium-oxide and mixed-oxide catalysts have achieved 95-98% FAME yields with similar structurally analogous non-edible feedstocks, vastly surpassing any catalytic performance (especially in terms of reusability and environmental friendliness) recorded for their homogeneous counterparts (Kabir, Rahman, & Islam, 2024); the proposed theoretical framework herein links physical catalyst characteristics, especially textural and surface attributes, to reaction efficiency and yield based on basic-acid and Langmuir-Hinshelwood based mechanisms and is not unfounded but

is fortified by precedents set in chemically analogous systems, though the specific applicability to *Cordia sebestena* oil remains empirically unverified. Simultaneously, it is crucial to acknowledge that significant bottlenecks continue to plague the broader biodiesel production sector, including feedstock quality variability, significant challenges in scaling-up laboratory-optimized processes to an industrial level, and considerable life-cycle carbon and energy costs associated with the synthesis, calcination and regeneration of catalysts; these factors suggest that, regardless of its promise at the laboratory bench scale, any application of the concept in this paper would require deliberate consideration of process intensification strategies and detailed techno-economic analyses before it could be considered viable at the industrial scale (Farooq, Bashir, & Zafar, 2025). Furthermore, the adoption of waste-derived or biomass-sourced heterogeneous catalysts over synthetically or petroleum-based feedstocks aligns this conceptual paper within the larger circular bioeconomy context wherein the conversion of readily available, inexpensive waste materials into catalytically active components used in the production of biodiesel contributes both to the avoidance of edible feedstocks and the utilization of waste streams, an approach widely regarded as critical for the future success of heterogeneous catalysis for biodiesel (Verma, Chatterjee, & Mondal, 2024); although the proposed use of the RSM-CCD design and LHHW-based kinetic modeling offers a statistically sound and mechanistically justified means of arriving at a set of optimized conditions and a predictive yield behavior model, it should be plainly admitted that all findings and suggestions presented in this paper are conceptual, based on analogous feedstock-catalyst systems, and would require laboratory-scale research efforts-synthesis and characterization of the catalyst as well as transesterification trials under the proposed optimized conditions-to be validated or modified.

Significance/Implications of the Study

There are three main areas in which this conceptual paper makes a significant and novel contribution: Academic: One primary contribution of the paper is its original and, in published literature, unique integration of existing academic frameworks - acid-base catalytic theory, Langmuir-Hinshelwood-Hougen-Watson surface-reaction kinetics, and heterogeneous catalysis surface-reaction theory - into a single, testable conceptual model. Critically, this integrated theoretical model is then specifically applied and adapted for the case of *Cordia sebestena* oil, thereby overcoming a recognized deficit in feedstock-specific catalytic literature and providing future researchers with a ready-made theoretical model and response variable set that can be directly implemented through optimization approaches such as

response surface methodology (RSM) (Farooq, Bashir, & Zafar, 2025); Industrial and Environmental: Another major contribution relates to its industrial and environmental utility, by proposing a feedstock-catalyst combination that has broad relevance for sustainable biodiesel production. By utilizing an ornamentally cultivated, non-food source like *Cordia sebestena*, the approach bypasses the food versus fuel dilemma, a persistent barrier to large-scale biodiesel implementation. Furthermore, the use of waste-derived or biomass-sourced heterogeneous catalysts - specifically the concept of exploiting low-cost, calcium-rich waste materials for their catalytically active properties - is in direct alignment with circular bioeconomy principles. It reduces reliance on conventional homogeneous alkali catalysts which produce large amounts of wastewater and generate a need for subsequent neutralization, significantly enhancing the environmental and cost profile of biodiesel production (Kabir, Rahman, & Islam, 2024); and Policy: Lastly, from a policy perspective, this conceptual framework has direct implications for the effective development and implementation of national biofuels policies. This is particularly salient given the policy landscape in countries such as India, where the drive toward renewable fuels, especially the twenty percent ethanol blending target in petrol, has moved significantly ahead of schedule (as evidenced by a stated 20% mandate achieved for the 2025-26 ethanol supply year) yet where progress on equivalent biodiesel blending targets remains far behind (under one percent as of recent reports). The successful advancement of diverse non-edible biodiesel feedstocks like *Cordia sebestena* oil, in conjunction with affordable and sustainable heterogeneous catalysts as envisioned in the conceptual framework, directly addresses a key feedstock constraint identified as hampering India's stated aims to achieve a five percent biodiesel blending target by 2030 (Advance Biofuel, 2026). Therefore, despite its conceptual nature, this paper stands to serve as a scientifically grounded foundation that can guide future funding allocations, research, and investment in biodiesel catalyst innovation and non-edible feedstock deployment.

CONCLUSION

Overall, this conceptual paper established an integrated theoretical and methodology framework for developing and optimizing novel heterogeneous catalysts for the transesterification of *Cordia sebestena* oil by proceeding systematically from an evidence-based introduction and through the literature review to an elaborated theoretical framework driven by acid-base catalytic theory, Langmuir-Hinshelwood-Hougen-Watson kinetics, and heterogeneous surface-reaction theory to clearly defined research gap, objectives and a future

research methodology consisting of catalyst synthesis, multi-technique characterization, RSM-CCD based optimization, and kinetic modeling, the expected results of which, based on previously achieved catalytic performances with Structurally similar heterogeneous catalysts from other non-edible feedstocks, would lead to a catalyst system which could achieve efficient FAME conversion and show remarkable catalytic stability after repeated usage by covering the aforementioned gap in knowledge concerning feedstock selectivity, standardization in optimization and reuse/stability performance (Show, Nguyen, Chang, Nguyen, and Chen, 2018); from an academic perspective, the herein proposed is an original, unaddressed feedstock-catalyst pairing that extends existing Heterogeneous Catalysis Theory into a complete new empirical realm by introducing a well-laid theoretical backdrop and experiment scheme which can directly implement by future scholars instead of derived starting from zero from basic principles and knowledge of science; From an industrial and environmental point of view, the concept above contribute toward a diversified non-edible, economically viable and widely available bio-feedstock production as well as promotes reuse of waste-based catalyst materials along with circular bioeconomy notion toward more economic and eco-sustainable biodiesel production compared with homogeneity catalysis based one (Verma and Sharma, 2023); Moreover, From a policy perspective, the achievement of this study contribute toward the expansion of diversity of non-edible and accelerated blending targets as in the current national strategy toward biofuel utilization when fully verified through an actual lab research, a renewable non-edible feedstock option with scientific support would then be available for policy- makers and industries to further promote biodiesel blending plans. Though a fully detailed study remains to be developed based on lab scale synthesis and catalytic performance verification toward optimal heterogeneous catalyst and reaction conditions described here, the herewith proposes is considered a complete, theoretically-driven and practically actionable starting points for unlocking fully the potential for converting botanic resources into a scientifically validated and industries relevant biodiesel feedstock.

REFERENCES

1. Advance Biofuel. (2026). *E20 ethanol India 2026: Market, growth and investment*. <https://advancebiofuel.in/e20-ethanol-india-investment-opportunity/>
2. Agu, C. M., Ani, K. A., Abiaziejje, P. O., Omeje, J. A., Ekuma, J. C., Umelo, U. E., Omukwu, O. H., Nwankwo, E. D., & Chinedu, M. P. (2024). Biodiesel production from waste cat fish oil using heterogeneous catalyst from cat fish bone: A viable waste

- management approach, and ANN modeling of biodiesel yield. *Waste Management Bulletin*, 1(4), 172–181. <https://doi.org/10.1016/j.wmb.2023.11.002>
3. Agunbiade, F. O., Adeosun, C. B., & Daramola, G. G. (2013). Nutritional properties and potential values of *Cordia sebestena* seed and seed oil. *Journal of Applied Sciences Research*.
4. Anr, N., Chen, Y., Setiawan, A., & Widyaningrum, T. (2019). Calcium oxide functionalized with strontium as heterogeneous transesterification catalyst for biodiesel production. *Fuel*, 241, 21–30. <https://doi.org/10.1016/j.fuel.2018.12.026>
5. Awad, S., El Rayess, Y., Zgheib, N., et al. (2025). An overview of biodiesel production via heterogeneous catalysts: Synthesis, current advances, and challenges. *Clean Technologies*, 7(3), 62. <https://doi.org/10.3390/cleantechnol7030062>
6. Buasri, A., Chaikut, N., Loryuenyong, V., Worawanitchaphong, P., & Trongyong, S. (2013). Calcium oxide derived from waste shells of mussel, cockle, and scallop as the heterogeneous catalyst for biodiesel production. *The Scientific World Journal*, 2013, Article 460923. <https://doi.org/10.1155/2013/460923>
7. Chen, C., Cai, L., Shangguan, X., Li, L., Hong, Y., & Wu, G. (2018). Heterogeneous and efficient transesterification of *Jatropha curcas* L. seed oil to produce biodiesel catalyzed by nano-sized $\text{SO}_4^{2-}/\text{TiO}_2$. *Royal Society Open Science*, 5(11), 181331. <https://doi.org/10.1098/rsos.181331>
8. dos Santos, H. C. L., Gonçalves, M. A., da Cas Viegas, A., Figueira, B. A. M., da Luz, P. T. S., da Rocha Filho, G. N., & da Conceição, L. R. V. (2022). Tungsten oxide supported on copper ferrite: A novel magnetic acid heterogeneous catalyst for biodiesel production from low quality feedstock. *RSC Advances*, 12(52), 33851–33862. <https://doi.org/10.1039/d2ra06923g>
9. Farooq, M., Bashir, T., & Zafar, M. (2025). Biodiesel: A comprehensive review of properties, catalyst types, and feedstock sources. *Fuel Processing Technology*.
10. Fortune Business Insights. (2026). *Biodiesel market size, share, industry analysis 2026–2034*. <https://www.fortunebusinessinsights.com/industry-reports/biodiesel-market-101631>
11. Jamil, F., Kumar, P. S. M., Al-Haj, L., Myint, M. T. Z., & Al-Muhtaseb, A. H. (2021). Heterogeneous carbon-based catalyst modified by alkaline earth metal oxides for biodiesel production: Parametric and kinetic study. *Energy Conversion and Management: X*, 10, 100047. <https://doi.org/10.1016/j.ecmx.2020.100047>

12. Kabir, M. H., Rahman, S., & Islam, M. R. (2024). Biobased heterogeneous renewable catalysts: Production technologies, innovations, biodiesel applications and circular bioeconomy. *Environmental Research*. <https://doi.org/10.1016/j.envres.2024.119345>
13. Kalyani, T., Prasad, L. S. V., & Kolakoti, A. (2023). Biodiesel production from a naturally grown green algae *Spirogyra* using heterogeneous catalyst: An approach to RSM optimization technique. *International Journal of Renewable Energy Development*, 12(2), 300–312. <https://doi.org/10.14710/ijred.2023.50065>
14. Kansedo, J., Lee, K. T., & Bhatia, S. (2009). Biodiesel production from palm oil via heterogeneous transesterification. *Biomass and Bioenergy*, 33(2), 271–276. <https://doi.org/10.1016/j.biombioe.2008.05.011>
15. Kolakoti, A., Setiyo, M., & Rochman, M. L. (2022). A green heterogeneous catalyst production and characterization for biodiesel production using RSM and ANN approach. *International Journal of Renewable Energy Development*, 11(3), 703–712. <https://doi.org/10.14710/ijred.2022.43627>
16. Lee, A. F., Bennett, J. A., Manayil, J. C., & Wilson, K. (2014). Heterogeneous catalysis for sustainable biodiesel production via esterification and transesterification. *Chemical Society Reviews*, 43(22), 7887–7916. <https://doi.org/10.1039/C4CS00189C>
17. Lee, A., & Wilson, K. (2024). Recent developments in heterogeneous catalysis for the sustainable production of biodiesel. *RMIT University Research Repository*.
18. Maroa, S., & Inambao, F. (2021). A review of sustainable biodiesel production using biomass derived heterogeneous catalysts. *Engineering in Life Sciences*, 21(11), 790–824. <https://doi.org/10.1002/elsc.202100025>
19. Mukhtar, A., Saqib, S., Lin, H., Hassan Shah, M. U., Ullah, S., Younas, M., Rezakazemi, M., Ibrahim, M., Mahmood, A., Asif, S., & Bokhari, A. (2022). Current status and challenges in the heterogeneous catalysis for biodiesel production. *Renewable and Sustainable Energy Reviews*, 157, 112012. <https://doi.org/10.1016/j.rser.2021.112012>
20. Ngige, G. A., et al. (2023). RSM optimization and yield prediction for biodiesel produced from alkali-catalytic transesterification of pawpaw seed extract: Thermodynamics, kinetics, and multiple linear regression analysis. *Digital Chemical Engineering*, 6, Article 100066. <https://doi.org/10.1016/j.dche.2022.100066>
21. Osman, A. I., et al. (2023). Heterogeneous catalytic transesterification for biodiesel production: Feedstock properties, catalysts and process parameters. *Process Safety and Environmental Protection*.

22. Precedence Research. (2026). *Biodiesel market size, share, and growth forecast 2026–2035*. <https://www.precedenceresearch.com/biodiesel-market>
23. Ravi, A., Gurunathan, B., Rajendiran, N., Varjani, S., Gnansounou, E., Pandey, A., You, S., Raman, J. K., & Ramanujam, P. (2020). A comprehensive review of heterogeneous catalyst use and importance in biodiesel production. *Environmental Technology and Innovation*, 19, 100906. <https://doi.org/10.1016/j.eti.2020.100906>
24. Sai, B. A. V. S. L., Madhu, S., Niju, S., Meera Sheriffa Begum, K. M., & Anantharaman, N. (2019). Biodiesel production from rubber seed oil using calcium oxide derived from eggshell as catalyst—Optimization and modeling studies. *Green Processing and Synthesis*, 8(1), 430–442. <https://doi.org/10.1515/gps-2019-0011>
25. Show, P. L., Nguyen, T. T., Chang, Y. K., Nguyen, T. D. P., & Chen, W. H. (2018). Bifunctional heterogeneous catalysts for biodiesel production using low-cost feedstocks: A future perspective. *IntechOpen*. <https://doi.org/10.5772/intechopen.86477>
26. Sundari, R. M., Rahman, S. F., & Kusuma, H. S. (2016). Deciphering the application efficacy of titanium dioxide mediated calcareous nanocatalysts towards biodiesel production. *Applications in Energy and Combustion Science*, 18, 100–110. <https://doi.org/10.1016/j.jaecs.2024.100253>
27. Tamoradi, T., Kiasat, A. R., Veisi, H., Nobakht, V., & Karmakar, B. (2022). RSM process optimization of biodiesel production from rapeseed oil and waste corn oil in the presence of green and novel catalyst. *Scientific Reports*, 12(1), 19652. <https://doi.org/10.1038/s41598-022-20538-4>
28. Verma, P., & Sharma, M. P. (2023). Heterogeneous catalysts for sustainable biofuel production: A paradigm shift towards renewable energy. *Journal of Cleaner Production*. <https://doi.org/10.1016/j.jclepro.2024.143452>
29. Verma, P., Chatterjee, S., & Mondal, S. (2024). Advancements in heterogeneous biobased and bio-composite catalysts: A comprehensive review on synthesis, characterizations, and applications in biodiesel production. *Bioenergy Research*. <https://doi.org/10.1007/s12155-025-10868-2>
30. Zanette, A. F., Barella, R. A., Pergher, S. B. C., Treichel, H., Oliveira, D., Mazutti, M. A., Silva, E. A., & Oliveira, J. V. (2011). Screening, optimization and kinetics of *Jatropha curcas* oil transesterification with heterogeneous catalysts. *Renewable Energy*, 36(2), 726–731. <https://doi.org/10.1016/j.renene.2010.08.028>