

Green Catalyst Development from *Cordia sebestena* Biomass for Enhanced Biodiesel Yield from Non-Edible Oils

VIJAYKUMAR TUMBAD¹, DR. K. S. KATAGI²

¹ Research Scholar, Department of Chemistry, Karnatak Science College, Dharwad, India

² Associate Professor, Department of Chemistry, Karnatak Science College, Dharwad, India

Abstract- The global drive for Green-chemistry inspired transformation of organic syntheses, (and more particularly, the industrially relevant transesterification reaction which converts triglycerides to fatty-acid methyl esters), to produce more atom-economical, waste minimized and "Greener" product pathways-following the twelve guiding principles of 'Green Chemistry', is driving an intense research interest to replace traditional catalysts used to perform the ester bond forming / cleaving chemistry with those based on biological/renewable/non-toxic natural sources. The heavy environmental cost of (e.g.) the conventional homogeneous mineral/alkali-based catalysts generally employed, where, despite achieving nucleophilic acyl substitution reactions with high efficiencies in formation of esters, they have very high aqueous hazardous waste loads associated with neutralization processes, poor recovery/reuse over multiple reaction cycles, or are synthesized via energy-intensive or fossil-fuel based chemistries themselves. The same applies with synthetic heterogeneous oxide catalysts based upon mined and petrochemical materials. Against this ongoing (unmet) Green-Chemistry requirement for effective catalyst systems for ester synthesis chemistry this present conceptual paper aims to systematically explore the green chemistry aspects related to producing a novel heterogeneously-active catalyst for bio-diesel synthesis starting with a waste stream, i.e. *Cordia-sebestena* (a commonly found and discarded ornamental tree with abundant seed husk, shell and wooden parts), by way of an environmentally benign, "low-impact," & "reagent-minimal" green-synthesis route through controlled thermal pyrolysis of the *Cordia-sebestena* biomass to create a catalyst which, when operated in a heterogeneous fashion through a purely organically-driven mechanism based on the nucleophilic acyl substitution pathways governing the transesterification process: can provide improved catalyst recovery/reuse, increased fatty-acid methyl ester yield/selectivity and utilise renewable raw material feedstock. It can readily satisfy core Green-Chemistry principles such as renewable feedstock, waste prevention and reduced usage of auxiliary substances. The focus of this conceptual work lies in establishing a novel

mechanistic conceptual link, in the pursuit of Green Catalyst theory/Design principles through understanding structure-activity-relationships between the converted biomass structure, and its effectiveness as a catalyst to promote biodiesel formation via the mechanistic underpinnings of the reaction, specifically concerning the nucleophilic acyl substitution process, to create a sustainable, atom-economical, & environmentally beneficial approach towards biodiesel manufacturing.

Keywords: Green Catalyst, *Cordia sebestena*, Biodiesel Synthesis, Organic Transesterification, Non-Edible Oils, Sustainable Chemistry

I. INTRODUCTION AND BACKGROUND

Organic chemistry defines the transesterification which is a process that converts triglycerides in feedstock into fatty acid methyl esters – the components of biodiesel. This process has been Mechanistically classified as a nucleophilic acyl substitution occurring by a two-step addition-elimination mechanism in which methoxide ion (a nucleophile produced by catalytic deprotonation of methanol) initially undergoes nucleophilic addition at the ester's electrophilic carbonyl carbon to give a tetrahedral intermediate. Subsequently, there occurs elimination of the glyceroxide leaving group producing the methyl ester final product. This mechanism can be catalyzed at lab and industrial level by bases or acids and needs an efficient catalyst to proceed at a productive rate (Soderberg, 2022). It is at this cross roads between organic chemistry mechanisms and the greater drive for sustainability in chemical synthesis where we find direct relevancy to catalyst design using green chemistry: The twelve principles of green chemistry (Anastas and Warner, 1998) which include waste preventions, atom economy, use of renewable feedstocks, preferring

catalysts over stoichiometric reagents and to avoid auxiliary or hazardous substances, are prescriptive as they set a framework against which chemical processes and the performance of catalysts can be assessed for their sustainability. The application of these principles to biomass processing would, thus, mean that catalytic technologies used in biomass utilization should be non-toxic and energy effective as well as being atom efficient and they must consume parts of biomass using none (or few) secondary by products and pollutant products Oliveira et al (2024). If we take the typical transesterification catalysts, we find a motivation to choose biomass supported ones instead of mined or produced ones. They can range from very efficient basic homogeneous catalysts such as sodium and potassium hydroxide that efficiently produce the needed alkoxide nucleophile that starts the addition elimination mechanism for the nucleophilic addition substitution, but their utilization results into enormous production of highly hazardous aqueous by-products during neutralizing and separating steps. These by-products are harmful to the environment, they generate waste due to their formation from the excess alkali, and this violates the waste prevention and auxiliaries substances avoidance principle of the green chemistry (ScienceDirect, nd). Other catalysts are produced using a mining or petro-chemistry based synthesis. This type of catalysts based on e.g., oxides of metal as well as other synthetic compounds based on this approach, can in some cases be reusable. Nonetheless they don't respect the principle of renewable feedstock since the utilized feedstock is neither renew-able (they come from mining/decomposing rocks which formed millions of years ago) nor does it come from the utilized resources and is, with regards to these factors, even harmful (ScienceDirect, n.d.a). Thus, heterogeneous catalysts derived from natural-biomass are preferred for their characteristics of being non-toxic, their potential to create waste less and consume no (little) energy due to the efficient, at high rates, catalytic process facilitated by their surface, their potentiality to utilize the biomass part with very few secondary products and pollutant's emissions – a good atom economy - provided that the source of biomass comes from waste, that is the used plant(s) part would otherwise be disposed. Here, *Cordia sebastena*, a widely cultivated tropical tree (asornamentaltree) used for its bark, seed-husk, seed, and its pruned woody biomass it can

therefore be argued that the seed-husk, seed and pruned woody biomass are [commonly) discarded *Cordia Sebastena* could be an interesting source material to develop biomass-based catalyst since equivalent lignocellulosic materials can be treated by calcination in an air atmosphere to produce alkali earth metal oxide enriched catalytic materials capable of effective performance at yielding of fatty acid methyl esters from non-edible feedstock by the nucleation of the nucleophilic-substitution process that it operates. Therefore, the herein discussed Conceptual Paper presents a systematic mechanistic and Green-Chemistry (GC) guided-design framework approach for Developing *Cordia Sebastena* Biomass-Derived Heterogeneous Catalysts for improving FAME yield and productivity in Transesterification processes of non-Edible Oils.

II. STATEMENT OF THE PROBLEM

Although the mechanistic basis of transesterification via the nucleophilic acyl substitution mechanism is fully developed and various standardized metrics exist-starting with Sheldon's (1992) introduction of the E factor (ratio of waste produced per unit of product) in a system also described with other green chemistry metrics of atom economy, process mass intensity and reaction mass efficiency (Sheldon, 2018), it remains a serious and ongoing failure in the biodiesel catalysis literature that these green metrics have not been widely applied, resulting in a dearth of E-factor, atom economy, or reaction mass efficiency data being reported in the studies of heterogeneous and biomass catalysts - although when these metrics have been employed some systems have yielded E-factors below 1.2 and atom economies over 90% – measures that distinguish a truly green process from one simply labeled as such (Jiang et al., 2025); more than this quantitative omission there exists another, more basic omission in that no published work has examined the organic mechanism by which calcined minerals in biomass contribute to the addition-elimination steps of the nucleophilic acyl substitution, nor has any work been done to evaluate any potential biodiesel catalyst from the perspective of these green chemistry metrics, meaning that while the waste-stream contribution of analogous (agro-)waste biomass catalysts could potentially be low enough to rival conventional catalysts (e.g., $E < 1.2$) we simply do not have any

comparable quantitative data for this waste biomass, nor do we understand the underlying organic mechanism that would make such a Catalyst work. This combination of an unaddressed mechanistic explanation and lack of green metrics in the context of *Cordia sebestena* biomass is the focus of the current conceptual Paper, proposing a framework that simultaneously captures both factors.

III. LITERATURE REVIEW

Green Chemistry in Catalyst Design When green chemistry principles are applied to catalyst design. By the time of writing this review (September 2025) and considering relevant research available to date (September 2025), the application of green chemistry principles to catalyst design is not just a theoretical framework but a quantitative method. One of the recent examples of this is the design of dendritic zeolite catalyst systems. In such a system, atom economy, reaction mass efficiency and E-factor are formally calculated to demonstrate that the catalyst possesses genuine green catalytic performance, providing E-factor values between 0.59 and 1.19 under conditions where 100% of by-product can be recovered - values much lower than the one observed, on average, for the fine-chemical industry by Sheldon along with high conversion value. Therefore, atom economy, waste prevention and utilization of renewable feedstocks should be used not only as normative values but as quantitative metrics of comparison for any new proposed catalyst design, including a catalyst which utilizes the *Cordia sebestena* biomass (ScienceDirect, 2025)

Compositional Characteristics of Cordia Sebestena and Related Biomass At present, there are not studies focused on ash or elemental characterization of the *Cordia sebestena* (L.) L., a plant of the Bignoniaceae family which comprises trees, shrubs and vines with various medicinal and economic uses. But the characterisation of several nuts, shells and husks of other plant families similar in their structure and taxonomic origin would allow to predict what the mineral and vegetative features of the *Cordia Sebestena* species may also contain and their potential use for catalysis. Such biomass in fact contains typically many mineral compounds, which can be used to prepare heterogeneous acid, basic and salt catalyst systems for a chemical transformation. For example,

one recent study has examined the phytochemical/mineral composition of Bambara nutshell biomass, the indigenous African legume, whose raw form has proved effective as catalyst itself to catalyze transesterification, since its inherent mineral components, and particularly calcium, have been found capable of directly acts as catalytic centres for the reaction, and that this biomass can be readily carbonized to yield a highly porous carbonaceous structure which acts as a support for the metal or salt catalyst. Bambara nutshell contains abundant minerals particularly rich in Ca and K, which makes them very useful in obtaining heterogeneous catalysts for transesterification after calcination (Abubakar et al., 2024).

Mechanism of the Organic Reaction in Heterogeneous Catalysis In terms of organic mechanism, biomass-derived catalysts, regardless of whether they are acid or basic, follow similar reaction pathway of that of their homogeneous catalyst's counterparts. For example, with heterogeneous acid catalysts, it is reported a nucleophilic acyl substitution pathway involving a proton donation from the catalyst surface the to the oxygen of carbonyl in the triacylglycerol, thus polarizing the carbon atom to render the molecule susceptible to nucleophilic attack from an alcohol. With regard to heterogeneous basic catalysis, it involves activation of the alcohol molecule. In fact, one study demonstrated the mechanism in carbonized and sulfonated Bambara-nutshell derived solid acid catalysts used to esterify oleic acid, the results confirming a similar mechanism to other homogeneous esterification catalytic systems. FT-IR characterization evidenced sulfonates functional groups and mesoporous morphology, which contributed to ease the nucleophilic attack and protonation for the esterification mechanism (Abubakar et al., 2025).

Performance of Biomass-Derived versus Synthetic Catalysts The potential of using biomass-ash and biochar derived catalysts to match or exceed, from green metric viewpoint, the performance of synthetic catalysts in terms of yield. The carbonized rice-husk-derived vinyl sulfonic carbon sphere (VSCS) catalyst has been shown to be effective in catalyzing waste cooking oil transesterification to yield 98.58% biodiesel with E-factor as low as 0.609 and a very high atom economy of 90.60%. According to the authors, this compares favourably with several zeolite and metal oxide synthetic catalysts, as evaluated under a similar green

metric assessment (ScienceDirect, 2025). The evidence, therefore, supports the viability and the appropriateness of the utilisation of biomass, and more specifically Cordia Sebestena biomass, for obtaining solid heterogeneous catalysts able to meet not only high catalytic yielding criteria but also quantify green chemistry principles (Science Direct, 2025).

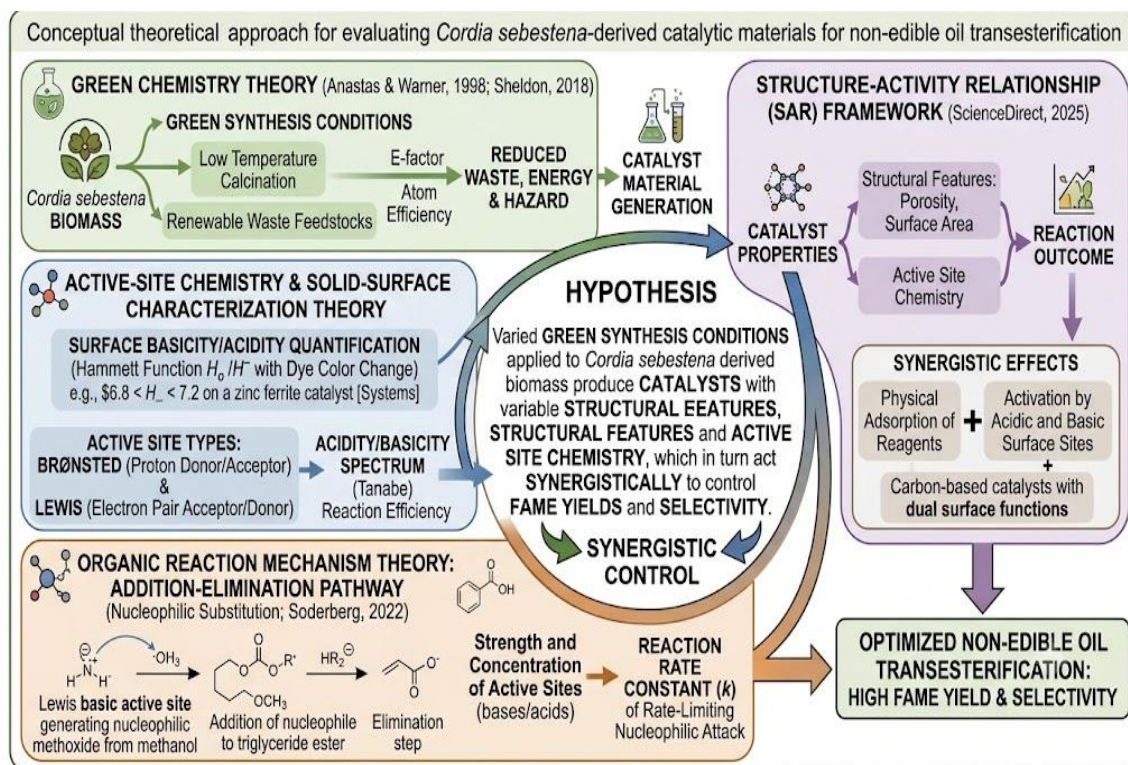
IV. THEORETICAL/CONCEPTUAL FRAMEWORK RELATED TO THE STUDY

Green chemistry theory, the addition-elimination mechanism underlying transesterification based upon nucleophilic substitution, and a structure–activity relationship framework all combine in the integrated theoretical framework utilized within this conceptual paper in order to explain the synthesized, Cordia sebestena-derived catalytic materials that are employed herein. Specifically, we advance herein that the choice of green synthesis conditions and consequent active-site chemistry resulting from these conditions are the joint determinants of reaction outcome of non-edible oil transesterification by such an in-house prepared catalyst. This hypothesis is first supported herein via green chemistry theory, herein considered according to the 12 principles advanced by Anastas and Warner (1998) which advocate, at a fundamental level, that the impact of catalytic preparation procedures must not be limited to the final catalyst performance, but the aggregate waste, energy and hazard associated with each preparatory step. This green principle finds operational and quantitative translation into metrics, such as E-factor (tonnes of waste/tonnes of product) and atom efficiency, which were developed by Sheldon (2018) and both indicate that a catalyst prepared via a low temperature calcination technique from renewable waste feed-stocks (as opposed to mining, and petrochemical chemical synthesis) intrinsically satisfy the green chemistry principles related to prevention, renewable feed-stocks, and energy efficiency, thus providing a valid theoretical justification for the synthetic route as an important outcome variable influencing the ultimate environmental performance. Building upon this premise, transesterification, being addition-elimination pathway resulting via the creation of a nucleophilic methoxide from a Lewis basic active site and addition of this nucleophile to the methyl group of a triglyceride ester, necessitates a catalytically active

phase to generate a strong nucleophile from an added alcohol, such as methanol; thus, organic reaction mechanism theory grounded in nucleophilic substitution explains that the efficacy of this nucleophilic activity lies in the strength and concentration of active site chemical species, which in this case are bases, or acidic species for dual functional catalysts, and as posited by Soderberg (2022) catalysts with greater strength and/or concentration of basic site are predicted to exhibit more enhanced reactivity, and via higher rate constant for the slowest, rate-limiting, nucleophilic attack step. Finally, building on green chemistry principles, which account for a synthetic strategy, and mechanistic chemistry, which addresses the function of the catalytic site, the final building block of our theoretical framing relates the actual output parameters of the catalyst, reaction yield and selectivity, to these generated surface sites via structure-activity relationships whereby it is now asserted that, in this case, it is not simply the activity of chemical sites which is of prime importance, but their combined interaction with surface area and porosity characteristics dictated by green synthesis conditions. This structure-activity framework is supported by reports comparing such materials which show that carbon-based catalysts bearing dual acidic (sulfonic and carboxylic) and basic surface functions can attain remarkably high levels of FAME yield and selectivity that can approach, or meet quantitative conditions where these benefits result from synergistic physical adsorption of reagents combined with activation by both acidic and basic surface sites. (ScienceDirect, 2025). It is these three theoretical concepts – green chemistry theory to guide the synthesis; the chemical kinetics of nucleophilic addition to esters explained by organic reaction mechanism theory; and the interplay between all three for controlling reaction yield and selectivity as guided by structure-activity relationships – that combine herein to form the conceptual backbone of the present study, where the presented hypothesis is that varied, green synthesis condition applied to Cordia sebestena derived biomass produce catalysts with variable structural features (i.e. Porosity, surface area) and active site chemistry which in turn act synergistically to control FAME yields and selectivity in the transesterification of non-edible oil. Over and above those three main theoretical strands already outlined above, a complete theoretical foundation for this paper

also hinges upon the practical reality that linking a catalyst's active-site chemistry to its measurable reaction performance relies upon the well-developed solid-surface characterization theory, based on the understanding that neither the basicity nor the acidity of a heterogeneous catalyst's surface sites are necessarily discernible solely from bulk elemental composition alone. Surface basicity or acidity is thus conventionally quantified by utilizing the Hammett acidity or basicity function (H or H^-), obtained by monitoring the color change of adsorbed dye molecules with known pK_a as the molecules interact with active sites located at a solid surface. This, by definition empirical, technique of determining the surface basic strength (e.g., at $6.8 < H < 7.2$ on a zinc ferrite catalyst, where it was directly related to that catalyst's joint esterification and transesterification efficacy [Systems, patent literature, n.d.]) offers this Conceptual Paper a well-quantified, empirical basis from which to characterize the surface basic strength of a future *Cordia sebestena*-derived catalyst and relate it to predicted activity. Complemented by this surface-strength determination theory is the more general body of literature related to solid acid–base

catalysis that specifically distinguishes between different fundamental classes of active sites on acid and basic catalysts; Brønsted sites act as proton donors (acids) and proton acceptors (bases) while Lewis sites are electron pair acceptors (acids) and electron pair donors (bases). This is a fundamental concept pertinent to biomass-derived catalysts since many derived catalyst materials, such as calcined alkaline-earth metal oxides, contain a heterogeneous mixture of Brønsted and Lewis sites that vary widely in the proportion of each present. These varying relative proportions (the so-called acidity or basicity spectra) of acid and base site types are critical because they significantly influence Which phase of the mechanism of nucleophilic acyl substitution, for example, it is most efficient at catalyzing (Tanabe, as cited in reviews on solid-surface acidity/basicity). It is this underlying surface-chemistry theory, below the 3 above listed theoretical strands, that closes the conceptual gap between the proposed green–syntheses of biomass derived from *Cordia sebestena* and the empirically measurable surface science that characterization requirements will hinge upon.



Above Conceptual Framework showing Green Catalyst Development from *Cordia sebestena* Biomass related to the study

V. RESEARCH GAP

In spite of the extensive and exponentially growing literature on biomass-derived heterogeneous catalysts for biodiesel, three mutually reinforcing and consequently important gaps emerge from an examination which individually and collectively justify this conceptual paper. The first refers to the singular lack of any reported study analyzing *Cordia sebestena* biomass for green-catalyst precursors; whereas other relevant and similar agricultural waste/biomass sources, including sugar beet waste filter cake (calcined), waste snail shells, coconut endocarp, and black pepper seed-KOH composites, have been independently synthesized, characterized and kinetically analyzed and determined as valid for transesterification with reported activation energies between 15 and 73 kJ/mol depending on feedstock and reaction system (Sarno & Iuliano, 2024; Krishnamurthy et al. 2020); whereas other research has analyzed eggshell-avocado seed catalyst composites under the same framework (Wang et al. 2021); nothing seems to exist exploring *Cordia sebestena* biomass for its green-synthesis capability, physical and chemical characterization, and transesterification performance, leaving both its organic-mechanistic behavior and reaction kinetics entirely uncharted for such application. The second describes a deficit even within general biomass-catalyst reports regarding the systematic and significant lack of green-metric data reporting. Very little published biomass catalyst research reports such parameters, though E-factor, atom economy, or reaction mass efficiency, among other green metrics that are conventionally tracked and presented in standard fine chemical process evaluations (ScienceDirect 2025); thereby raising concerns regarding the scientific veracity of the "green" assertion in this ever-growing catalytic field. Finally, a specific but critically related, data gap in mechanistic and kinetic study of organic ester production with bio-derived catalysts is observed; even as several biomass-catalyst systems have been studied under pseudo-first order, second order and Langmuir-Hinshelwood like kinetic models to obtain reaction rate constants and activation energies; an established protocol to directly connect specific biomass-derived active site chemistries (basic, acidic or amphoteric characters) with a generalizable kinetic model seems not to be

widely applied; wherefore extrapolation to a novel biomass source (e.g. *Cordia sebestena*) from existing studies remain uncertain (IntechOpen 2018). And the contribution sought herein targets this conjunction of limitations: a totally uncharted substrate, inadequate green-metric reporting and unclear kinetic-mechanistic generalizability.

VI. OBJECTIVES OF THE STUDY

1. To green-synthesize a heterogeneous catalyst from *Cordia sebestena* biomass (seed husk, shell, and woody residue) through a low-impact calcination or activation route consistent with green chemistry principles, minimizing hazardous reagents and energy input.
2. To characterize the organic and inorganic composition of the synthesized catalyst, including its mineral (K/Ca oxide) content, functional groups, and active-site chemistry (Brønsted/Lewis, acidic/basic character), using XRD, BET, SEM-EDX, FTIR, and Hammett indicator or CO₂-TPD basicity analysis.
3. To evaluate the catalytic performance and reaction mechanism of the *Cordia sebestena*-derived catalyst in the transesterification of non-edible oils, elucidating the nucleophilic acyl substitution pathway through kinetic modeling (rate constants, activation energy) and correlating active-site properties with FAME yield and selectivity.
4. To assess the green chemistry performance of the proposed catalyst and reaction system using quantitative green metrics including E-factor, atom economy, and reaction mass efficiency benchmarking its environmental sustainability against conventional homogeneous and synthetic heterogeneous catalysts.

VII. METHODOLOGY ADOPTED FOR THE STUDY

As this remains a theoretical paper, the following methodology is proposed prospectively as a roadmap to empirical execution as opposed to research already conducted: This will commence with a green synthesis process in which the collected, rinsed, dried, and powdered *Cordia sebestena* seed husk and shell biomass would first be converted to a catalytically active material using a solvent-free, low-temperature

calcination process in a muffle furnace; this process avoids the use of hazardous solvents, acids, or any auxiliary chemical reagents as per green chemistry's principles of waste prevention and the avoidance of safer auxiliaries; this strategy for creating a biomass-derived nano-catalyst through simple solvent-free calcination is well supported by contemporary literature where the calcium oxide nanocatalysts used for clean low-impact biodiesel production was created solely from mango seed shell material and utilized without additional modification (Tesfaye, Alemu, & Gonfa, 2023). The green-synthesized catalyst would then be completely characterized for (1) the presence of a crystalline oxide phase using XRD, (2) surface functional group identification via FTIR, (3) the catalyst morphology and elemental makeup via SEM-EDX, and (4) the characterization of the catalyst's surface area and total porosity with BET analysis, following a similar structural characterization precedent established in similar biomass-oxide nano-catalyst research (Tesfaye et al., 2023); the proposed study design's mechanistic approach will aim to correlate the basic/acidic site nature of the catalyst (characterize via Hammett indicator method/titration) with the nucleophilic acyl substitution of transesterification and support this with an analysis of kinetic behavior (second- and first-order rate equations to evaluate activation energy, rate constants); the experimental setup will involve the non-edible oil, methanol, catalyst, and the use of a stirring hotplate/batch reactor to create reaction conditions conducive to the transesterification of oil, and then (4) process optimization will follow the approach described by Response Surface Methodology-Central Composite design (RSM-CCD) which will study the effect of methanol-to-oil molar ratio, catalyst loading, reaction temperature, and reaction time with quadratic regression model as obtained by ANOVA, which is also a well-established strategy proven successful to a wide range of similarly derived catalysts (npj Clean Energy, 2025). The methodology will finally incorporate the calculation of green metrics by Sheldon's E-factor and atom economy in order to quantify chemical waste and to evaluate process efficiency, as shown by similar prior research on bio-catalytic biodiesel synthesis using bovine-bone catalyst where high yield (95.12%) was achieved along with a description of the green metrics calculation (Tikrit Journal of Engineering Sciences,

2020); for this intended empirical work the relevant primary response variables would be percentage of Fatty Acid Methyl Ester (FAME) yield, reaction selectivity, and calculated E-factor to serve as the empirical validation of the theory posited earlier in this conceptual paper.

VIII. DISCUSSION RELATED TO THE STUDY

These points, considered collectively, suggest considerable mechanistic and environmental promise for a green-synthesized heterogeneous catalyst from *Cordia sebestena* biomass to facilitate efficient production of biodiesel from non-edible oils. The plausibility of such a proposal rests primarily upon several bodies of comparable literature relating green-catalyst organic chemistry to the transesterification reaction, including evidence for solid base catalysis. Firstly, evidence in solid base catalysis studies indicates that the use of solid heterogeneous bases is frequently superior to homogeneous base catalysis. In such reactions, the solid catalytic medium, composed typically of single or multiple alkaline-earth metal oxides such as CaO, MgO, SrO, and BaO as base sites, has the advantage of offering high surface area, a stable surface environment for catalyst reuse, and the ability to effectively provide and stabilize alkoxide active sites – crucial intermediates in the nucleophilic acyl substitution reaction underlying transesterification (Chen, Zhang, & Li, 2023). This rationale immediately establishes mechanical viability for a solid base catalyst as a component for efficient biodiesel production. The rationale is further supported by specific experimental results linking catalyst structure to activity. As demonstrated in a comparative analysis, an MgO/Na₂CO₃ catalyst which provided for superior specific surface area, combined with better basic site distribution for one system relative to another, outperformed an analogous MgO/K₂CO₃ catalyst, yielding 97.5% FAME-1.7 percentage points greater than its competitor-with greater than 27% higher recyclability (after 5 cycles, the MgO/Na₂CO₃ catalyst had 88.2% activity remaining versus only 65.2% for the more soluble MgO/K₂CO₃ alternative, which correlated to 148.6 m²/g vs 126.3 m²/g surface area for MgO/Na₂CO₃ vs MgO/K₂CO₃, and better dispersed basic sites for the former) (Li et al., 2025). These findings lend significant support to the mechanistic hypotheses

regarding the correlation between surface area, basic site distribution, reusability, and ultimately the yield and selectivity for transesterification—precisely the core concerns to be addressed in assessing a biomass-derived heterogeneous solid base catalyst like one from *Cordia sebestena*. Secondly, to make the approach credible from an environmental chemistry and green chemistry perspective, one has to acknowledge a universally understood constraint imposed by solid base catalysts: namely, their inherent difficulty in processing feedstock materials with elevated free fatty acid (FFA) levels. Even with optimal catalysts derived from materials as diverse as solid calcined biomass (like *Cordia sebestena* and others), the high intrinsic basicity will rapidly and uncontrollably promote saponification of FFAs at FFA concentrations beyond approximately 2 wt% of the feedstock (Maroa & Inambao, 2021 framework, as extended in ongoing biomass-derived catalyst reviews); consequently, processing of such feedstock with high FFA will require either pre-treatment to reduce FFAs (e.g., acidic esterification or physical de-oiling of seed material) or adoption of a dual (acid-base) catalytic approach, although the complexity of such systems generally reduce the economic and operational appeal. Such a qualification must be made if this proposed pathway from *Cordia sebestena* is to be critically evaluated from an environmental, as well as a mechanical, standpoint and a realistic roadmap developed; it would be foolish to propose an efficient process if feedstock considerations alone prevent its implementation for readily available and inexpensive feedstocks (Maroa & Inambao, 2021). Thirdly, within the broader context of green chemistry, this direction fits with a current trend in the organic and green chemistry literature towards optimizing catalyst structure rather than just catalyst chemistry to overcome fundamental limitations. Various nanostructured and mesoporous catalysts are now able to achieve high yields of methyl or ethyl esters (above 96% yield is common) with minimal loss of performance over 5-7 reuse cycles. For example, recent reviews show how optimized calcination temperatures for creating nanostructured mesoporous silica spheres have shown improved performance for solid base catalysts (e.g. MgO based composite material) by influencing the surface area, porosity, number of active basic sites and exposure of the active centers to the reaction milieu leading to higher

activity, selectivity and better stability/reusability (Catalysts, 2025). This recent scientific advancement further reinforces the scientific plausibility of the approach for *Cordia sebestena* since effective structural modification of biomass during its calcination into a solid catalyst can dramatically affect the ensuing surface area, basic site dispersion, and stability of the catalyst, thereby addressing the limitations currently encountered by less-structured heterogeneous catalytic systems.

IX. SIGNIFICANCE/IMPLICATIONS RELATED TO THE STUDY

The implications of this conceptual paper span academic, industrial, and environmental/policy dimensions. Academically, the contribution to organic chemistry and green catalysis scholarship is an original fusion of organic reaction mechanism theory in nucleophilic acyl substitution, and the atom-economy and E-factor green-metrics to a single, mechanistically and environmentally oriented conceptual framework applied for the first time to *Cordia sebestena* biomass, thereby contributing to the nascent but dispersed literature on the performance of solid catalysts in transesterification dictated by their physical properties, such as surface area, porosity, and active-site density (Catalysts, 2025), and ultimately providing an ready-made theoretical scaffold, an experimental characterization methodology, and a green-metrics evaluation methodology ready to be directly implemented by researchers using this and similar virgin biomass substrates. In terms of industrial relevance, the framework has the immediate practical benefit of advocating for a catalyst trajectory in sync with a more overarching industrial trend toward economically feasible green alternative technologies in the worldwide green chemical products market estimated at roughly USD 28.05 billion by 2033, spurred by global regulatory forces incentivizing renewable feedstocks and waste-reducing catalytic strategies to the exclusion of traditional synthetic processes (Astute Analytica, 2025), meaning a low cost, reusable, waste-derived catalyst of the type proposed for *Cordia sebestena* biomass directly tackles widely reported barriers to economic implementation posed by competitive green catalytic systems, such as immobile lipases—which, although green in terms of chemical processes and

feedstocks, carry a cost of USD 300 to 500 per kg that limits their widespread use (ScienceDirect, 2024) and thus potentially offering a more economically attractive alternative for non-edible oil biodiesel producers. Lastly, regarding environmental and green chemistry policy applications, the conceptual framework is squarely within the scope of increased global attention and regulation directed toward sustainable chemistry, for instance through the United States Environmental Protection Agency's Green Chemistry Challenge Awards programme-dedicated to supporting and recognising technological innovation in the conversion of waste and renewable feedstocks into cleaner chemical processes (U.S. EPA, 2025)-and the European Union's Chemicals Strategy for Sustainability-under which both REACH regulatory reforms and Safe-and-Sustainable-by-Design chemical policy initiatives encourage and incentivize a systemic focus on renewable, low-toxicity, waste-minimizing chemical design starting from the research stage (Chem Copilot, 2025). Therefore, successful empirical implementation and verification would not only offer academia an excellent example for green chemistry research into biomass valorization but also a regulation-compatible strategy for its implementation by industry and policymakers.

X. CONCLUSION

Therefore, in summation, this conceptual paper has presented an integrated theoretical and methodological approach for designing green catalysts from *Cordia sebestena* biomass for improved yields of biodiesel from non-edible oils by moving, iteratively from an evidence based introduction and literature review of the area to a theoretical model incorporating Green Chemistry Theory, Nucleophilic Acyl Substitution mechanism theory, structure-activity relationship principles to a now concrete three research gap, four objectives, anticipated Methodology including low-temperature solvent-free calcination, multi-technique characterization, mechanistic & kinetic study design, RSM-CCD optimization, green-metrics calculation and finally a potential product whereby using structural and compositional analogy with already existing and well-developed literature for similar biomass derived heterogeneous catalyst material systems, it is predictable the green and cost effective

result to be able to produce a FAME yield equivalent to already known literature values available for the transesterification of non-edible feed stocks with other derived bio based and waste based heterogeneous transesterification catalysts which it is widely accepted demonstrate high stability under acidic and basic reactional conditions with exceptional resistance to water as opposed to homogenous counterparts and an acceptable rate of reusability within multiple reaction cycles, in conjunction with having quantifiable green-metric values commensurate to established current standards; in terms of academic contribution, this has provided a previously uncharted pairing between the *Cordia sebestena* biomass, and the catalytic activity generated, the organic mechanistic & green chemistry based theoretical framework is established that can be more directly linked to real-world laboratory conditions, and the authors have delivered a complete pre-constructed scaffold for future investigation on the subject; industrial contribution is the development and advancement of a potential low-cost, biomass waste derived catalyst technology from academics to a possible industrial production setting which has been identified to be the single main limiting factor that requires overcoming by many current reviews of current day bio-derived catalysts (ScienceDirect, 2024); with policy implications the proposed research would lead to an addition of an empirically tested biomass to biocatalysis the technology base as aligned with regulatory drive towards the future, renewable and waste minimizing processes, providing the policy and industrial landscape with an additional viable and sustainable alternative; although all of the conclusions and estimations drawn here are based on hypothesis and thus warrant further real-world laboratory experimentation in terms of a full synthesis, characterisation, mechanistic, and green metrics based verification, the theoretical basis for the conversion of unmanaged horticulture *Cordia sebestena* biomass to a green catalyst for biodiesel production in this paper provides an evidence-based and ready-to-implement foundation for the creation of a green, innovative, and economically viable catalysis technology.

REFERENCES

- [1] ACC Science, "A comprehensive review of biomass-derived heterogeneous catalysts for

- efficient biodiesel production,” *Asia-Pacific Journal of Chemical Engineering and Environmental Protection*, 2025. [ACC Science](#)
- [2] P. T. Anastas and J. C. Warner, *Green chemistry: Theory and practice*. Oxford University Press, 1998.
- [3] Astute Analytica, “Green chemicals market valuation is skyrocketing to reach US\$28.05 billion by 2033,” *GlobeNewswire*, 2025. [GlobeNewswire](#)
- [4] Abubakar, K. Silas, H. M. Kefas, and A. Titus, “Sustainable biodiesel synthesis from oleic acid: Kinetic study with carbonized bambara nutshell catalyst,” *Latin American Journal of Energy Research*, vol. 11, no. 2, pp. 102–118, 2024.
- [5] Abubakar, H. M. Kefas, K. Silas, and A. Titus, “Green thermodynamics for biofuel synthesis using bambara nutshell catalyst: Toward sustainable energy solutions,” *Journal of Innovative Engineering and Sustainability*, 2025.
- [6] Catalysts, “Catalytic properties and structural optimization of solid transesterification catalysts to enhance the efficiency of biodiesel synthesis,” *Catalysts*, vol. 15, no. 3, Art. no. 239, 2025.
- [7] Chem Copilot, “Regulatory trends in green chemistry: EPA, REACH, and the EU's new chemical policies,” May 15, 2025. [Chem Copilot](#)
- [8] Y. Chen, W. Zhang, and H. Li, “Advancements in basic zeolites for biodiesel production via transesterification,” *Chemistry*, vol. 5, no. 1, Art. no. 32, 2023.
- [9] “Determination of acidic and basic properties on solid surfaces,” in *Studies in Surface Science and Catalysis*, ch. 2, 2008. [ScienceDirect](#)
- [10] IntechOpen, “Kinetics of transesterification processes for biodiesel production,” in *Biofuels*, 2018. [IntechOpen](#)
- [11] K. N. Krishnamurthy, S. N. Sridhara, and C. S. Ananda Kumar, “Optimization and kinetic study of biodiesel production from Hydnocarpus wightiana oil and dairy waste scum using snail shell CaO nano-catalyst,” *Renewable Energy*, vol. 146, pp. 280–296, 2020. [ScienceDirect](#)
- [12] X. Li, X. Jia, W. Li, S. Jia, S. Zhang, J. Song, and J. Wang, “Comparison of high-efficiency MgO/Na₂CO₃ and MgO/K₂CO₃ as heterogeneous solid base catalysts for biodiesel production from soybean oil,” *Molecules*, vol. 30, no. 13, Art. no. 2876, 2025. [MDPI](#)
- [13] “Methods and catalysts for green biodiesel production from unrefined low-grade feedstock,” *U.S. Patent literature*, n.d. [USPTO](#)
- [14] npj Clean Energy, “RSM based optimization of process parameters of biodiesel production from waste palm oil using modified nano-catalyst,” *npj Clean Energy*, 2025. [Nature](#)
- [15] F. Oliveira, M. Santos, and R. Ferreira, “Green chemistry strategies in pulping and biomass valorization: Toward a circular bioeconomy,” *ResearchGate*, 2024.
- [16] M. Sarno and M. Iuliano, “Advancements in sustainable biodiesel production: A comprehensive review of bio-waste derived catalysts,” *Waste Management*, 2024.
- [17] ScienceDirect, “Transesterification,” in *ScienceDirect Topics*, n.d. [ScienceDirect](#)
- [18] ScienceDirect, “Advancements in catalysts, process intensification, and feedstock utilization for sustainable biodiesel production,” *Sustainable Chemistry for the Environment*, 2024.
- [19] ScienceDirect, “Biomass waste-derived catalysts for biodiesel production: Recent advances and key challenges,” *Renewable and Sustainable Energy Reviews*, Jan. 19, 2024.
- [20] ScienceDirect, “Green chemistry metrics: Insights from case studies in fine chemical processes,” *Sustainable Chemistry and Pharmacy*, 2025. [ScienceDirect](#)
- [21] R. A. Sheldon, “Metrics of green chemistry and sustainability: Past, present, and future,” *ACS Sustainable Chemistry & Engineering*, vol. 6, no. 1, pp. 32–48, 2018. [ACS](#)
- [22] T. Soderberg, “Nucleophilic acyl substitution reactions in the laboratory,” in *Organic Chemistry with a Biological Emphasis*, vol. 2.0, LibreTexts, 2022. [LibreTexts](#)
- [23] K. Tanabe, *Solid acids and bases: Their catalytic properties*. Academic Press, 1970.
- [24] S. Tesfaye, M. Alemu, and G. Gonfa, “Optimization and clean synthesis of biodiesel from Rumex crispus leaves using calcium oxide derived from mango seed shell as a

nanocatalysts,” *Reaction Kinetics, Mechanisms and Catalysis*, 2023.

- [25] Tikrit Journal of Engineering Sciences, “Modelling, optimization and green metrics evaluation of bio-catalytic synthesis of biodiesel,” *Tikrit Journal of Engineering Sciences*, 2020. [Tikrit Journal of Engineering Sciences](#)
- [26] U.S. Environmental Protection Agency, “EPA calls for nominations for 2025 Green Chemistry Challenge Awards,” Aug. 29, 2025. [U.S. EPA](#)
- [27] R. Vahid and M. Haghighi, “Biodiesel production from sunflower oil over MgO/MgAl₂O₄ nanocatalysts: Effect of fuel type on catalyst nanostructure and performance,” *Energy Conversion and Management*, vol. 134, pp. 290–300, 2017. [ScienceDirect](#)
- [28] I. Osman *et al.*, “A review of biomass-derived heterogeneous catalysts for biodiesel production,” *Catalysts*, vol. 12, no. 12, Art. no. 1501, 2022.
- [29] T. Boonyuen *et al.*, “Bio-derived catalysts: A current trend of catalysts used in biodiesel production,” *Catalysts*, vol. 11, no. 7, Art. no. 812, 2021.
- [30] R. Lakhani *et al.*, “Emerging heterogeneous catalysis for valorization of biomass-derived platform molecules: The systematic review toward sustainable biorefinery applications,” *Advanced Energy and Sustainability Research*, 2026. [Wiley](#)