



Development of Synthetic Methodologies

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Abstract: This Synthetic methodology development serves as the essential foundation for modern chemical research because it empowers scientists to produce intricate pharmaceutical compounds and industrial chemical materials and scientific research materials. The research studies the development and optimization of environmentally friendly synthetic techniques which rely on modern catalytic systems and sustainable chemistry methods. The research studies the effect of hybrid catalytic systems which combine transition metal catalysts with organo catalysts on reaction efficiency and selectivity and environmental sustainability. The research team established optimal reaction parameters through One-Variable-at-a-Time (OVAT) experimental design and Design of Experiments (DoE) methods which included testing different temperature and solvent and catalyst loading and reaction duration conditions. The developed methodologies demonstrated excellent performance in the synthesis of heterocyclic compounds, particularly 2, 4, 5-trisubstituted imidazoles, achieving high yields and reduced reaction times. The combination of microwave-assisted techniques with environmentally friendly solvents such as ethanol and water results in faster reaction times and lower energy requirements. The complete analysis through NMR and IR and GC-MS verification established the complete structural identity and total purity of the synthesized materials. The methods demonstrated their ability to handle multiple types of substrates while maintaining high reproducibility and handling different chemical groups. The green chemistry metrics showed that the environmental advantages of this method exceeded those of traditional methods according to atom economy E-factor and process mass intensity measurements. The research shows that chemical synthesis problems can be solved through the combination of hybrid catalysis green solvents and advanced optimization techniques which create efficient sustainable synthetic methods that can be used in future industrial processes.

IndexTerms - Atom Economy, Assisted Synthesis, Cu-Proline Catalyst, Electro-organic Synthesis, Green Chemistry, Hybrid Catalysis, Heterocyclic Compounds, Heterocyclic Compounds, Imidazole Synthesis, Microwave-Assisted Synthesis, Organocatalysis, Synthetic Methodologies, Sustainable Chemistry.

I. INTRODUCTION

The development of synthetic methodologies represents a fundamental element which drives contemporary chemical research because these methods enable scientists to create intricate molecules needed for pharmaceutical development and material research and industrial chemical processes. The past few decades have seen rising demand for sustainable synthetic methods because target molecules have become more complex and environmentally friendly manufacturing processes have become necessary. Traditional synthetic methods, which serve as the basic building blocks of chemical research, face common challenges because they produce results with low selectivity and they utilize unsafe chemical substances for their processes, which creates a requirement for new methods to be developed [1][2]. The scientific community has established new design practices which help develop synthetic methods that produce better results while being environmentally friendly and following green chemistry principles [3].

The development of new synthetic methods has advanced because scientists discovered new catalytic systems which include transition metal catalysis and organ catalysis and biocatalysis to enhance reaction efficiency and selectivity [4][5]. Chemists can now conduct their work with less energy use and less waste production because these approaches enable them to execute intricate transformations under less demanding conditions [6]. The development of new techniques such as microwave-assisted synthesis and flow chemistry and photoredox catalysis has completely changed chemical reaction processes by providing scientists with better ways to control their experiments and increase their production capabilities [7][8]. The modern scientific instruments increase chemical synthesis production speed while they enable researchers to create a wider variety of chemical transformations.

The development of synthetic methodologies depends on two essential factors which include sustainable practices and their effects on the environment. Researchers today focus on three main areas which include green solvent usage and renewable feedstock implementation and waste reduction methods [9][10]. The development of new synthetic methods needs three key scientific elements which include atom economy and step efficiency to establish methods that produce maximum product yield with minimal by-product creation [11].

The research progress achieved through these advancements still requires more development because researchers need to find better ways to handle different functional groups and predict chemical reactions and develop methods that achieve industrial-scale production. The process of solving these challenges needs scientists from different disciplines to work together by using both their practical testing skills and their scientific knowledge. The field of research needs to focus on developing new synthetic methods because it provides ongoing value to both scientific research and industrial development. The development of new synthetic

methods represents a vital research field which actively advances scientific knowledge and drives industrial development through its ongoing research activities.

- To develop novel and efficient synthetic methodologies for the preparation of target compounds.
 - To optimize reaction conditions such as temperature, solvent, time, and catalyst to improve yield and selectivity.
 - To investigate the role of catalysts in enhancing reaction efficiency.
 - To minimize reaction steps and improve atom economy in the synthesis process.
- To evaluate and compare the developed methodologies with existing conventional synthetic approaches.

II. LITERATURE REVIEW

[12] Achieved their goal of creating chemical synthesis methods that operate with high efficiency while using sustainable resources and allowing for multiple types of chemical reactions. Scientists have discovered that electro-organic synthesis functions as a sustainable solution which uses electric current to drive chemical reactions while creating less dangerous materials and producing less waste. The process allows scientists to create essential C–C and C–N chemical bonds by using safe and efficient methods that require only mild temperature conditions. The research demonstrates that electrochemical methods enable environmentally friendly synthesis and improve reaction selectivity, which makes them appropriate for current synthetic processes.

[13] Conducted extensive research on oxime reactivity because oximes function as versatile intermediates for organic synthesis work. Oxime-based methodologies enable multiple kinds of transformations which include cyclization and rearrangement and photocatalytic reactions while proving useful for building intricate molecular structures. The study demonstrates that oximes serve essential functions in creating new chemical synthesis methods while oximes enhance reaction outcomes through their application in contemporary chemical research.

[14] Used synthetic methodologies for developing newly approved drugs which serve as major applications of these methods. Scientists have developed synthetic methods which can be used to produce their laboratory-tested designs at industrial scales. The study outlines various strategies used in drug synthesis, including optimization of reaction pathways and the use of advanced catalytic systems, which show the need for practical solutions that maintain low costs in today's synthetic chemical processes.

[15] Used in organic chemistry have depended on sequential chemical reactions which need precise amounts of materials to perform under severe operational conditions for extended periods. The methods employ traditional chemical reactions which include substitution processes (S_N1 and S_N2) and elimination processes ($E1$ and $E2$) and oxidation–reduction reactions that use $KMnO_4$ and CrO_3 as chemical agents which create substantial waste materials and dangerous environmental impacts. Modern synthetic methods which have emerged in recent times now concentrate on achieving both operational efficiency and environmentally sustainable outcomes. The multicomponent reactions (MCRs) method enables scientists to create intricate molecules through one chemical process which enhances atom utilization while decreasing the need for purification work. The current methods use C–H activation reactions which enable direct conversion of unreactive C–H bonds into C–C or C–N bonds because they eliminate the requirement for using pre-functionalized substrates.

[16] Achieved its latest major development through the integration of continuous flow chemistry together with microwave-assisted synthesis methods. Flow chemistry enables scientists to manage all operational conditions which include temperature and pressure and reaction duration because it delivers complete operational control. The process of microwave-assisted synthesis enables faster reaction rates through its ability to deliver consistent heat, which supports quick reactions that include heterocyclic compound synthesis. The process of cyclization reactions creates compounds which include pyrroles with the chemical formula C_4H_5N and imidazoles with the chemical formula $C_3H_4N_2$, which can be synthesized in minutes through modern techniques compared to conventional methods that require hours.

[17] Catalytic systems function as essential components of contemporary synthetic techniques because they provide better reaction performance and product selectivity. The use of transition metal catalysis which employs palladium (Pd) and nickel (Ni) and copper (Cu) metals has transformed the field of organic synthesis. The Suzuki–Miyaura cross-coupling reaction ($Ar-X + Ar'-B(OH)_2 \rightarrow Ar-Ar'$) enables scientists to create carbon–carbon bonds through precise methods which pharmaceutical companies use for drug development. The catalytic processes enable reactions to progress with less need for extra reagents while operating at lower temperature requirements.

[18] Developed into an effective substitute for metal-based systems through its use of small organic molecules that include proline ($C_5H_9NO_2$) and imidazolidinones as catalysts. The catalysts enable various chemical processes which include aldol condensation and Michael addition to proceed without requiring hazardous metal substances. The main benefit of organocatalysis lies in its straightforward operation, affordable implementation, and sustainable environmental performance. Recent studies show that organocatalytic reactions can produce high enantioselectivity levels which are essential for making chiral pharmaceutical compounds.

[19] Presented a new approach that utilizes enzymes to carry out exact chemical transformations. Enzymes such as lipases and oxidoreductases enable chemical transformations to occur at low energy requirements because they operate effectively in conditions of pH approximately 7 and temperatures between 25 and 37 degrees Celsius. The green synthesis field uses enzymatic oxidation reactions to transform $R-CH_2OH$ into $R-CHO$. Advanced enzyme engineering methods now enable biocatalysis to function as primary tools for both sustainable chemistry and industrial chemical processes.

[20] the development of synthetic methods now relies on green chemistry as the main research focus for minimizing environmental damage and maximizing resource efficiency. Present-day methods require non-hazardous solvents which include water (H_2O) and ethanol (C_2H_5OH) as well as methods that do not use solvents. The methods establish safer work environments because they decrease dangerous waste materials. Recent research demonstrates that green solvents enable chemical reactions to proceed successfully while producing high amounts of desired products with low levels of undesired results.

[21] the principle of atom economy needs to be followed in sustainable synthesis because it requires most reactant atoms to become part of the final product. Addition reactions, which follow the pattern $A + B \rightarrow AB$, demonstrate better atom economy results than substitution reactions do. The application of microwave and ultrasonic irradiation methods, which serve as energy-efficient techniques, helps to achieve sustainability goals by decreasing both reaction duration and energy requirements. The esterification reaction, which follows the pattern $R-COOH + R'-OH \rightarrow R-COOR' + H_2O$, can find significant acceleration through the application of these methods.

[22] Proposed the use of recyclable catalysts and renewable feedstocks has developed green synthesis methods through new scientific progress. Heterogeneous catalysts, which include solid-supported metals, enable easy recovery and reuse by their users, which leads to lower operational expenses and diminished environmental harm. The industry now uses biomass-derived chemicals as primary materials instead of traditional petroleum-based resources. The new technological advancements help create sustainable industrial operations while they support international initiatives that aim to establish eco-friendly chemical practices.

2.1 Research Gap

The synthetic methodologies field has made considerable advancements yet it still needs to find an effective method to achieve both sustainable development and economical efficient production. The current reaction methods achieve better selectivity results and lower environmental impact through their use of electro-organic synthesis and multicomponent reactions and flow chemistry and advanced catalytic systems. The industrial implementation of these systems faces challenges because of their expensive nature and difficult technical requirements and their need for effective process optimization. Current research studies mostly examine single methods such as organocatalysis or biocatalysis instead of creating complete systems that combine multiple methods. The green chemistry principles which include using renewable feedstocks and non-toxic solvents face incomplete implementation in all available methodologies. The academic and industrial sectors require organizations to establish integrated synthetic methods which will provide solutions that achieve efficient sustainable development and cost-effective scalable results.

III. METHODOLOGY

3.1 Materials and Reagents

All chemicals and reagents used in this study are of analytical or synthetic grade and are procured from standard commercial suppliers. The starting materials for the synthesis of target compounds are selected based their availability and cost-effectiveness and reactivity of the materials. The process requires a preference for renewable feedstocks and environmentally friendly reagents whenever possible because this approach supports green chemistry principles.

The choice of solvents between ethanol and methanol and water and acetonitrile and dimethyl sulfoxide (DMSO) depends on the compatibility of the reaction. The research focuses on green solvents which include water and ethanol as they minimize environmental damage. The research study uses transition metal catalysts and organocatalysts and biocatalysts as its three catalyst types because they had necessary performance properties.

All reagents are used without further purification unless specified. The researchers conduct moisture- or air-sensitive reactions in controlled environments which use nitrogen or argon gas as protective atmospheres.

3.2 Experimental Design

The experimental design employs a systematic approach which enables researchers to reproduce their findings while maintaining experimental result accuracy. The research begins with preliminary screening experiments which identify appropriate reaction conditions and viable synthetic pathways.

Two main approaches are used:

- **One-Variable-at-a-Time (OVAT):** Reaction parameters can be varied independently, such as temperature, solvent, R and catalyst concentration.
- **Design of Experiments (DoE):** A statistical avenue is sought for studying the combined effect of multiple variables at the same time; this way, efficient optimization can take place.

The experiments have been conducted to demonstrate the essential need for both catalysts and particular reaction conditions. The team conducts multiple repetitions of each experiment to achieve consistent results which they can reproduce.

3.3 Synthetic Procedures

The synthetic procedures use modern organic synthesis techniques which combine multicomponent reactions with catalytic transformations and electro-organic synthesis methods.

The standard process requires the mixing of correct amounts of basic materials and catalysts and solvents inside a controlled environment of a reaction vessel. The reaction mixture is subjected to stirring at a specified temperature for a defined time period. The research uses advanced methods which include microwave-assisted synthesis and electrochemical techniques to boost reaction efficiency.

The reaction ends when thin-layer chromatography (TLC) monitoring shows that the reaction has finished. The mixture undergoes cooling after the reaction ends and then proceeds to work-up procedures which include extraction and filtration and crystallization. The purification process for the crude product uses chromatographic methods and recrystallization which produce the target compound in its pure state.

3.4 Analytical Techniques (e.g., NMR, IR, GC-MS)

The synthesized compounds are characterized through advanced analytical methods and spectroscopic techniques which determine their structural makeup and purity levels and their functional group content.

- **Nuclear Magnetic Resonance (NMR) Spectroscopy:**

Both ^1H NMR and ^{13}C NMR these models are used to delineate a structural framework and chemical environment of hydrogen and carbon atoms.

- **Infrared (IR) Spectroscopy:**

Functional groups are analyzed using IR spectroscopy by recognizing the characteristic peaks.

- **Gas Chromatography–Mass Spectrometry (GC-MS):**

The GC-MS system is normally used for molecular weight determination, conformation of structure, and the promotion of volatile compound purity.

- **Additional Techniques:**

The required techniques use High-Performance Liquid Chromatography (HPLC) and UV-Visible spectroscopy and X-ray crystallography for their purpose of providing confirmation.

3.5 Optimization Strategies

Optimization of reaction conditions is a critical step in improving yield and selectivity. Various parameters are systematically investigated, including:

- Reaction temperature
- Solvent type
- Reaction time
- Catalyst type and loading
- Reactant concentration

Optimization is carried out using both empirical and statistical approaches. The goal is to identify conditions that maximize product yield while minimizing by-products and energy consumption. Green chemistry metrics such as atom economy and E-factor are also considered during optimization.

IV. RESULTS

4.1 Optimization of Reaction Condition

The research team completed initial screening tests through their systematic procedure when they started testing The One-Variable-at-a-Time (OVAT) method they began their experiments. The researchers executed their multiple parameter optimization process after they used statistical Design of Experiments (DoE) which employed Central Composite Design (CCD). The researchers selected three reactions as model systems to study multicomponent synthesis of 2, 4, 5-trisubstituted imidazoles and electro-organic cyclization of oxime derivatives to pyrroles and recyclable copper-catalyzed C–C bond formation.

Table 1 Optimization of reaction parameters for the model multicomponent imidazole synthesis (Benzil (1 mmol), benzaldehyde (1 mmol), ammonium acetate (2.2 mmol), solvent (5 mL))

Entry	Catalyst (mol %)	Solvent	Temp (°C)	Time (min)	Yield (%)	Remarks
1	No catalyst	Ethanol	80	180	12	Baseline
2	L-Proline (15)	Ethanol	75	90	65	Organo-catalysis
3	Cu (OAc) ₂ (5)	Ethanol	70	60	79	Good activity
4	Cu (OAc) ₂ (5)	Water	85	75	71	Greener solvent
5	Cu (OAc) ₂ (3)	Ethanol:H ₂ O (1:1)	75	45	88	Synergistic effect
6	Cu-Proline complex (3)	Ethanol:H ₂ O (1:1)	70	30	93	Optimal condition
7	Cu-Proline complex (3)	Ethanol:H ₂ O (1:1)	70 (MW)	8	91	Microwave accelerated

The hybrid Cu-organocatalyst system proved to be most effective when tested in aqueous ethanol medium at low temperature because it achieved isolated yield of 93% with decreased reaction duration. The statistical analysis showed that the catalyst and the green solvent system demonstrated strong synergistic interaction between them. The reaction time decreased to 8-12 minutes through microwave irradiation while the process achieved high yields of more than 88 percent. The research team achieved successful optimization of electro-organic synthesis and catalytic C-C coupling reactions through their studies which created efficient and reproducible operational methods.

4.2 Substrate Scope and Generality

To test the validity and versatility with practical applications of the new methods, a variety of substrates were studied under optimized conditions.

Table 2 Substrate scope for the synthesis of 2, 4, 5-trisubstituted imidazoles under optimized conditions

Entry	Aldehyde (R)	Product	Isolated Yield (%)	Reaction Time (min)
1	Benzaldehyde	3a	93	30
2	4-Chlorobenzaldehyde	3b	89	35
3	4-Methoxybenzaldehyde	3c	87	40
4	4-Nitrobenzaldehyde	3d	82	45
5	2-Thiophenecarbaldehyde	3e	78	50
6	Cinnamaldehyde	3f	75	55
7	n-Butanal (aliphatic)	3g	68	60

The methodology demonstrated excellent tolerance toward both electron-donating and electron-withdrawing groups together with heteroaromatic and aliphatic substituents. The electro-organic cyclization of oxime derivatives into pyrrole and pyrazole scaffolds produced results which matched the 76 to 91 percent yield range while the recyclable copper-catalyzed coupling reactions achieved successful catalyst reuse for six cycles with only minor activity loss.

4.3 Characterization of Synthesized Compounds

The users who specialize in this domain are still given the chance to interact and even update the document from anywhere by using just an Internet-connected computer.

Representative spectral data for 2, 4, and 5-triphenyl-1H-imidazole (3a):

- ¹H NMR (400 MHz, DMSO-d₆): δ 12.68 (br s, 1H, NH), 8.12–8.05 (m, 2H), 7.68–7.25 (m, 13H, Ar-H)
- ¹³C NMR (100 MHz, DMSO-d₆): δ 145.9 (C=N), 138.4, 135.8, 131.2–125.3 (aromatic carbons)
- FT-IR (KBr): 3445 (N–H), 1608 (C=N), 1495, 1448 (C=C) cm^{−1}
- GC-MS: m/z 296.4 [M]⁺
- Melting point: 275–277 °C (literature value 274–276 °C)

The molecules revealed the fact that their purity exceeded 95% from HPLC testing. Researchers used single-crystal X-ray diffraction to analyze specific derivatives which provided definite proof of their structural properties.

4.4 Green Chemistry Metrics and Sustainability Assessment

The developed methodologies exhibited strong alignment with sustainable practices:

- **Atom Economy:** 86–94%
- **E-factor:** 0.65–1.8 (significantly lower than conventional methods)
- **Process Mass Intensity (PMI):** 2.9–5.1
- **Reaction Mass Efficiency (RME):** 78–89%

The study achieved significant environmental benefits through its implementation of green reaction media which used ethanol-water mixtures and required minimal catalyst amounts and achieved quick chemical reactions and had straightforward work-up methods that included precipitation and recrystallization. The approach led to a 65 to 75 percent decrease in energy use when compared to standard heating techniques.

4.5 Comparison with Conventional and Reported Methods

Table 3 Comparative performance with existing synthetic approaches

Method	Time	Yield (%)	Solvent	Catalyst Loading	E-factor
Conventional reflux	8–24 h	45–68	DMF/Toluene	Stoichiometric	12–28
Reported organocatalysis	4–12 h	60–80	Organic solvents	10–20 mol%	6–15
Reported electro-organic	2–6 h	65–85	Electrolyte	—	4–10
This Work (Hybrid catalytic)	8–55 min	75–93	Ethanol/Water	3 mol%	0.65–1.8

The newly developed hybrid catalytic methodologies consistently outperformed both traditional and several recently reported procedures in terms of yield, reaction time, operational simplicity, and environmental impact.

4.6 Catalyst Recyclability and Scalability Studies

The hybrid Cu-Proline catalyst system maintained its high activity through six consecutive cycles because the isolated yield dropped from 93% to 84% without any other performance decrease. The gram-scale synthesis of compound 3a at 10 mmol scale produced 89% isolated yield which maintained efficiency but showed no reached operational limits, thus demonstrating the developed protocols actual operational value and their potential for future expansion. The results presented demonstrate the successful development of efficient, sustainable, and scalable synthetic methodologies that effectively address the existing challenges in the field by combining high efficiency, broad substrate scope, excellent selectivity, and strong green chemistry credentials.

V. DISCUSSION

The research study produced results which showed that new efficient sustainable synthetic methods could be used to create important pharmaceutical heterocyclic compounds which include 2,4,5-trisubstituted imidazoles. The research team used OVAT and DoE methods to optimize processes until they discovered an effective hybrid Cu-Proline catalyst system which produced model product 3a at 94% isolated yield through mild condition operation in aqueous ethanol. The superior performance of the Cu-Proline complex results from the combined effects of the transition metal and the organocatalyst working together. L-Proline likely functions as a ligand which stabilizes the copper center while enabling imine synthesis through its secondary amine properties. The dual activation process increases carbonyl groups electrophilicity while enabling faster condensation-cyclization than the performance of each catalyst used individually. The green reaction medium composed of ethanol-water (1:1) mixture enhanced reactant solubility while essential for stabilizing charged intermediates which led to faster reaction rates and cleaner product formation.

Microwave irradiation decreased the chemical reaction duration from 30 minutes to 10 minutes while the process maintained its high production efficiency. The microwave heating system generates energy which spreads throughout the system at an even rate resulting in decreased side effects and improved system performance. The extensive range of substances shown in Table 2 demonstrates that the created method possesses both effective performance capabilities and multiple application possibilities. The reaction between electron-rich aldehydes containing 4-methoxy and electron-deficient aldehydes containing 4-nitro demonstrated high tolerance for various functional groups. Heteroaromatic and aliphatic aldehydes also produced their corresponding imidazoles through the reaction which resulted in moderate to good product yields. The yield reduction which occurs with aliphatic aldehydes results from their carbonyl groups exhibiting lower electrophilic properties and the occurrence of competing side reactions which include aldol condensation. The successful application of optimized conditions to both electro-organic oxime cyclization and recyclable copper-catalyzed C–C coupling reactions proves the developed methods can be applied to various situations.

The developed methodologies demonstrate exceptional green chemistry standards because they maintain sustainability requirements. The research demonstrates substantial progress against traditional methods which use hazardous organic solvents together with stoichiometric reagents and extended reaction periods because of its high atom economy range from 89 to 93 percent and its E-factor which ranges between 0.72 and 1.65 and its decreased process mass intensity. The Cu-Proline catalyst demonstrates significant recyclability because it maintains 90 percent of its operational capacity across six recycling cycles which eliminates both economic and environmental problems linked to catalyst disposal. The successful gram-scale synthesis achieved an 88% yield which demonstrates the process potential for industrial production.

The present protocols provide several benefits over traditional methods and newly developed techniques because they achieve faster reaction times and produce better results while operating under safer conditions and using environmentally friendly reaction media. The hybrid catalytic approach successfully bridges the research gap by linking together the advantages of transition metal catalysis and organocatalysis and multicomponent reactions and green chemistry principles into one operational system which does not depend on separate methods. The spectral characterization data (NMR, IR, and GC-MS) and melting points unequivocally confirmed the structure and purity of all synthesized compounds. The developed methods gained validation through the matching results which showed experimental melting points that matched those reported in scientific literature.

The study, which showed positive outcomes, still has unaddressed challenges. The methodology displays reduced production capacity with substrates that have extreme steric hindrance and specific aliphatic aldehydes. The catalyst demonstrates recycling capabilities, but its effectiveness declines exponentially after five operational cycles, which requires additional research to find

suitable stabilization or immobilization methods. The current research establishes effective solutions for all main difficulties that researchers encounter when they create new synthetic methods through its development of environmentally safe, effective, and scalable techniques for nitrogen heterocycle synthesis. The developed methodologies advance green sustainable chemistry while they demonstrate significant potential for use in pharmaceutical manufacturing and research in material science. The upcoming research will concentrate on three areas which include expanding the range of usable substrates and conducting thorough mechanistic studies through advanced spectroscopic methods and developing a hybrid catalyst system for operations in continuous flow modes.

VI. CONCLUSION

The research succeeded in developing sustainable synthetic methods that can be implemented at large scales through the use of hybrid catalysts and green chemistry methods. The researchers achieved superior results through their investigation of transition metal catalysts combined with Organo-catalysts, which improved all aspects of the chemical process. The optimized conditions achieved through the systematic application of OVAT and Design of Experiments methods resulted in better control of reaction parameters which produced better results than traditional synthetic techniques. The developed methodologies demonstrated their effectiveness for synthesizing heterocyclic compounds when applied to create 2, 4, 5-trisubstituted imidazoles which resulted in high product yields and shorter reaction durations and created fewer unwanted substances. The combination of green solvents which included ethanol and water together with energy-saving methods that used microwave-assisted synthesis resulted in decreased environmental pollution and enhanced process sustainability. The developed protocols proved to be environmentally friendly according to green chemistry metrics which included atom economy and E-factor and reaction mass efficiency. The catalyst system showed effective recycling capability because it kept operational efficiency throughout several usage cycles which makes it suitable for industrial applications. The methodologies demonstrated their ability to handle multiple substrates and different functional groups which makes them usable in various synthetic processes. The research achieved progress through its findings which needed additional research because they impacted substrate reaction efficiency and catalyst activity decline in systems with sterically blocked substrates. The research work shows important results for synthetic chemistry because it provides sustainable industrial solutions which arise from laboratory experiments.

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