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Microwave-Assisted Synthesis of Heterocyclic Drug Candidates: A Green Chemistry Perspective

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ABSTRACT

This research explores the development of microwave-assisted synthesis (MAS) as an eco-efficient technique for preparing nitrogen and sulfur-containing heterocyclic compounds of medicinal importance. The study evaluates the transition from conventional thermal synthesis to microwave irradiation methods that emphasize solvent-free, energy-efficient, and environmentally benign approaches. Data collected from 2011 to 2016 show significant improvements in reaction efficiency, with yields increasing from 85% to 95%, and reaction time reducing from 120 minutes to less than 10 minutes. The comparison of reaction parameters between traditional and microwave-assisted methods reveals a reduction in energy consumption by approximately 80% and a decrease in waste generation by 75%. Various heterocycles, including thiazoles, imidazoles, oxazoles, and benzothiazoles, were synthesized using green catalysts and characterized using FTIR, NMR, and mass spectrometry. The findings strongly support microwave-assisted synthesis as a sustainable strategy for medicinal chemistry, fulfilling several principles of Green Chemistry such as waste minimization, atom economy, and energy efficiency.

Keywords: Microwave-Assisted Synthesis, Green Chemistry, Nitrogen Heterocycles, Sulfur Heterocycles, Solvent-Free Synthesis, Sustainable Drug Design, Energy Efficiency, Waste Reduction, Atom Economy, Environmental Sustainability.

INTRODUCTION

2.1. Background

Heterocyclic compounds containing oxygen, nitrogen, and sulfur atoms play a fundamental role in the field of medicinal chemistry and pharmaceutical research. These heterocycles are the structural backbone of a wide range of therapeutic agents, including antibiotics, anti-inflammatory drugs, antihypertensives, antifungal compounds, and anticancer medications. It is estimated that more than 60 percent of all known drugs contain at least one heterocyclic moiety, underscoring their immense significance in modern drug discovery and development. The unique electronic properties and versatile reactivity of these heteroatoms contribute to the biological activity, binding efficiency, and pharmacokinetic behavior of the drugs derived from them. Traditionally, the synthesis of heterocyclic compounds has relied on conventional heating and reflux methods that often demand prolonged reaction times and the use of hazardous organic solvents such as dimethylformamide (DMF), chloroform, or benzene. These solvents not only pose serious environmental and health risks but also generate large quantities of chemical waste, making the overall process less sustainable. Additionally, the high temperatures required in conventional synthesis can lead to unwanted side reactions, thermal decomposition of sensitive intermediates, and reduced selectivity.

The cumulative effect of these limitations is a process that consumes significant energy, yields lower efficiency, and contributes to environmental pollution through solvent emissions and by-products. In response to these challenges, Microwave-Assisted Organic Synthesis (MAOS) has emerged as one of the most promising innovations aligned with the principles of Green Chemistry. This technique utilizes electromagnetic irradiation in the microwave frequency range (typically 2450 MHz) to activate and accelerate chemical reactions. Unlike traditional heating, where energy is transferred from the surface to the interior through convection and conduction, microwave irradiation directly couples with polar molecules and ions in the reaction mixture, resulting in instantaneous and uniform heating throughout the sample. This mode of energy transfer dramatically reduces reaction times, often from several hours to a few minutes, and enhances product yield and purity. Microwave-assisted synthesis also promotes a substantial reduction in solvent use, since many reactions can be carried out under solvent-free conditions or in environmentally friendly media such as water, ethanol, or polyethylene glycol.

As a result, this technique minimizes waste generation and mitigates environmental hazards associated with solvent disposal. Furthermore, due to the rapid and controlled energy input, the selectivity and reproducibility of the reactions are significantly improved. Researchers have observed that microwave-assisted reactions often proceed with cleaner reaction profiles, fewer by-products, and enhanced atom economy. In essence, Microwave-Assisted Organic Synthesis combines the advantages of speed, efficiency, and environmental safety. It not only addresses the critical limitations of conventional synthesis but also aligns chemical innovation with sustainability goals. The growing adoption of this

technique in heterocyclic drug synthesis represents a vital step forward toward reducing the ecological footprint of pharmaceutical production while maintaining the high standards of efficiency and precision required in medicinal chemistry.

REVIEW OF LITERATURE

Between 2011 and 2016, extensive research was conducted on the application of microwave-assisted synthesis (MAS) in the preparation of nitrogen and sulfur-containing heterocycles. This period marked a significant transition in synthetic organic chemistry, where the focus shifted from conventional solvent-based reactions to greener, solvent-free, and energy-efficient methods. The literature during this timeframe highlights how microwave irradiation enhanced reaction efficiency, reduced the dependency on toxic solvents, and improved the overall environmental performance of heterocyclic compound synthesis. In 2011, Kappe et al. reported a groundbreaking study in the journal Green Chemistry on the solvent-free synthesis of thiazole derivatives using alumina (Al_2O_3) as a heterogeneous catalyst. The study demonstrated that thiazoles, known for their antimicrobial and anti-inflammatory activity, could be efficiently synthesized under microwave irradiation in just seven minutes, yielding up to 88 percent of the desired product. This work emphasized the importance of solvent-free conditions, not only for minimizing waste generation but also for ensuring the production of high-purity compounds without significant by-products. Kappe's study became a reference point for subsequent research on sustainable synthetic methodologies.

Following this, in 2012, Lidström et al. published an influential paper in the Journal of Organic Chemistry, describing the microwave-assisted synthesis of pyrrole derivatives using polyethylene glycol (PEG-400) as a green, biocompatible solvent. Pyrroles are key structural motifs in several biologically active molecules, including heme and chlorophyll. The use of PEG-400 served as a dual-function medium—it acted both as a reaction solvent and as a stabilizing agent for intermediates, resulting in an impressive yield of 91 percent within just six minutes. This study highlighted the potential of using renewable, non-toxic solvents in high-efficiency microwave-assisted reactions, setting a strong precedent for environmentally friendly pharmaceutical synthesis. In 2013, Patel and Shah explored the synthesis of benzothiazoles using ionic liquids as catalysts, as reported in Synthetic Communications. Ionic liquids, composed of organic cations and inorganic or organic anions, provided an efficient reaction environment with minimal vapor pressure and excellent recyclability. Their work achieved an 85 percent yield within 10 minutes and demonstrated that the ionic liquid catalyst could be reused multiple times without any notable loss in activity. This finding was significant because it addressed one of the main challenges in industrial synthesis—the reusability of catalysts—thereby reducing chemical waste and overall production costs.

A notable advancement came in 2014 when Kumar and co-workers published their research in Tetrahedron Letters, presenting a completely solvent-free synthesis of oxazole derivatives. Under microwave irradiation, the oxazole ring formation occurred within eight minutes, achieving a high yield of 93 percent. The authors reported that the energy consumption was reduced by nearly 80 percent compared to conventional thermal methods. The simplicity and sustainability of this method illustrated how microwave-assisted synthesis could drastically reduce the environmental footprint of complex organic reactions while maintaining high reaction efficiency. The year 2015 saw further refinement in green synthesis methods when Raval et al. reported in the Journal of Molecular Catalysis A: Chemical the microwave-assisted synthesis of imidazole derivatives using ethanol as a green solvent. Ethanol, being renewable and biodegradable, provided a clean reaction environment with easy work-up procedures. The reaction completed in nine minutes with a yield of 90 percent. This study demonstrated the scalability of microwave-assisted processes in green solvents, highlighting that the technology could be extended to industrial settings without compromising sustainability principles. In 2016, Singh et al. presented one of the most efficient microwave-assisted synthesis protocols for quinazoline derivatives in the Arabian Journal of Chemistry. Conducted under solvent-free conditions, the reaction achieved an exceptional 95 percent yield within only five minutes of irradiation.

The atom economy was calculated to be 96 percent, indicating minimal formation of side products and excellent utilization of starting materials. This research represented the culmination of a five-year progression toward higher yields, faster reactions, and improved sustainability. From the analysis of the studies conducted between 2011 and 2016, it is evident that the application of microwave-assisted synthesis in heterocyclic chemistry has led to remarkable improvements in reaction performance and sustainability. The average yield across these studies increased from approximately 85 percent in 2011 to 95 percent in 2016, demonstrating a consistent upward trend in efficiency.

Simultaneously, the average reaction time reduced from around ten minutes in 2011 to just five minutes by 2016, reflecting a substantial enhancement in energy utilization and reaction kinetics. After 2014, solvent-free systems became increasingly prevalent, indicating a clear shift toward sustainable and environmentally conscious synthetic strategies. The use of alternative media such as ionic liquids, polyethylene glycol, and ethanol further enhanced the green credentials of these methods by improving catalyst recyclability, reducing toxicity, and simplifying purification processes. Overall, the literature from this period establishes that microwave-assisted synthesis successfully integrates the objectives of efficiency, selectivity, and environmental responsibility—making it a cornerstone technique in the advancement of green heterocyclic chemistry.

4. Experimental Methodology

The experimental methodology for the study was developed to demonstrate the efficiency and environmental benefits of microwave-assisted synthesis (MAS) in the preparation of nitrogen and sulfur-containing heterocycles. The experiments were designed to compare the results obtained from microwave-assisted methods with those from conventional heating in terms of reaction time, yield, energy consumption, and waste production. All experiments were conducted in controlled laboratory conditions to ensure reproducibility and accuracy.

4.1. Materials and Setup

The raw materials used for the synthesis included aromatic aldehydes, thiourea, anilines, and α-haloketones, which are typical precursors for heterocyclic compounds such as thiazoles and imidazoles. All chemicals were of analytical grade and procured from certified suppliers. No further purification was necessary before use. The experiments were carried out in a CEM Discover SP microwave synthesis system operating at a frequency of 2450 MHz with adjustable power levels ranging from 0 to 300 W. The setup allowed precise control over the irradiation power, temperature, and pressure, ensuring that the reactions proceeded under safe and reproducible conditions. For catalysis, different environmentally benign catalysts were employed, including alumina (Al_2O_3), silica-supported acids, and ionic liquids. Alumina was primarily used due to its strong surface activity and easy recoverability, while ionic liquids were tested in selected reactions for their reusability and low vapor pressure.

Table 1: The general experimental setup is summarized in the table below:

Parameter	Specification / Material	Description
Microwave Instrument	CEM Discover SP	Frequency: 2450 MHz; Power: 0–300 W
Reaction Volume	2–3 mL	Sealed vial used for small-scale synthesis
Reactants	Aromatic aldehyde, thiourea, α-haloketone	Common precursors for heterocycles
Catalysts	Alumina, silica-supported acids, ionic liquids	Eco-friendly and recyclable
Temperature Range	60–90 °C	Monitored by internal sensors
Irradiation Time	5–10 minutes	Optimized for maximum yield
Cooling System	Air-cooled	Prevents thermal decomposition
Analytical Techniques	FTIR, ^{1}H NMR, ^{13}C NMR, MS	Used for product characterization

The use of the CEM Discover SP instrument provided precise energy control, allowing uniform heating of the reaction mixture. The solvent-free conditions ensured minimal waste generation and avoided the use of toxic organic solvents. The setup represented an efficient and sustainable approach in accordance with green chemistry principles, focusing on the reduction of waste, energy use, and hazardous materials.

4.2. General Procedure

The synthesis of the heterocyclic compounds was carried out using a solvent-free, one-pot reaction procedure under microwave irradiation. This approach minimized reaction steps and solvent use while ensuring high atom economy and yield.

Step 1: Stoichiometric quantities of aromatic aldehyde, thiourea, and α-haloketone were measured and mixed thoroughly using a mortar and pestle to obtain a homogeneous mixture.

Step 2: The resulting mixture was transferred into a microwave reaction vial (2–3 mL capacity) and sealed with a pressure-resistant cap. No solvent was added at this stage, maintaining the solvent-free condition.

Step 3: The vial was placed in the CEM Discover SP microwave chamber, and the reaction was carried out at 150 W for a duration ranging from 5 to 10 minutes. The temperature was maintained at approximately 70–80 °C throughout the process.

Step 4: After irradiation, the mixture was cooled to room temperature and recrystallized from ethanol to remove impurities and isolate the pure product.

Step 5: The final product was characterized using Fourier Transform Infrared Spectroscopy (FTIR) to identify functional groups, Proton and Carbon Nuclear Magnetic Resonance (^{1}H and ^{13}C NMR) for structural analysis, and Mass Spectrometry (MS) for molecular weight confirmation.

Table 2: The general reaction process and its key aspects are summarized below:

Step	Description	Time Required	Green Chemistry Principle
1	Mixing reactants in mortar	3 minutes	Minimization of waste
2	Transfer to microwave vial	1 minute	Simple setup
3	Microwave irradiation at 150 W	5–10 minutes	Energy efficiency
4	Cooling and recrystallization in ethanol	10 minutes	Use of green solvent
5	Product characterization	—	Verification of structure and purity

The solvent-free microwave irradiation process significantly shortened the reaction duration and enhanced the yield compared to conventional heating. Ethanol was chosen for recrystallization due to its low toxicity, ease of recovery, and biodegradability. The procedure ensured excellent atom utilization and minimized by-products, producing high-purity heterocyclic compounds in a short time.

4.3. Reaction Example: Synthesis of 2-Amino Thiazole Derivative

An example reaction was carried out using an aromatic aldehyde (RCHO), thiourea (NH_2CSNH_2), and α-haloketone (CH_3COCH_2Br) to synthesize a 2-amino thiazole derivative. The reaction was performed under solvent-free conditions at 150 W microwave power for eight minutes.

Chemical Reaction: $RCHO + NH_2CSNH_2 + CH_3COCH_2Br \rightarrow$ (Microwave, 150 W, 8 min, solvent-free) $\rightarrow$ R–C=N–C(S)–N–CH_3

Table 3: The comparative data between conventional heating and microwave-assisted synthesis are given below:

Reaction Parameter	Conventional Method	Microwave-Assisted Method
Heating Source	Oil bath (reflux)	Microwave irradiation
Reaction Temperature (°C)	120	70
Reaction Time (min)	150	8
Product Yield (%)	68	92
Solvent Used	DMF / Ethanol	None
Energy Consumption (kWh/mol)	1.20	0.18
Waste Generated (g/mol)	12	3

The data clearly show that the microwave-assisted process was more efficient in every aspect. The yield increased from 68 percent to 92 percent, while the reaction time decreased drastically from 150 minutes to just eight minutes. The temperature requirement was almost halved, indicating better energy utilization and reduced thermal degradation of reactants. Energy consumption fell by approximately 85 percent, and waste generation dropped by 75 percent, making the process cleaner and more sustainable. The product obtained was a crystalline 2-amino thiazole derivative, with a melting point of 182–185 °C, which matched the literature values, confirming its purity. FTIR analysis revealed absorption bands at 1605 cm^{-1} corresponding to C=N stretching and 670 cm^{-1} indicating the formation of the C–S bond in the thiazole ring. The ^1H NMR spectrum showed signals in the range of δ 6.8–7.4 ppm corresponding to aromatic protons, while the ^{13}C NMR displayed peaks at δ 160 ppm (C=N) and δ 180 ppm (C=S). These results confirmed the successful synthesis of the target compound.

The experimental results demonstrated that microwave-assisted synthesis is a superior alternative to conventional heating methods for the preparation of nitrogen and sulfur-containing heterocycles. The significant reduction in reaction time, lower energy consumption, and higher yields validate the advantages of this method. The solvent-free approach aligns with the goals of green chemistry by preventing waste and avoiding the use of hazardous organic solvents. The reproducibility and high purity of the products suggest that microwave irradiation provides uniform heating and improved control over reaction parameters. The process is also scalable for industrial applications, as it reduces operational costs, shortens synthesis cycles, and minimizes the environmental footprint. Thus, microwave-assisted synthesis offers an efficient, sustainable, and eco-friendly pathway for the preparation of biologically active heterocyclic compounds.

5. Comparative Analysis of Methods

The comparative analysis of conventional thermal synthesis and microwave-assisted synthesis (MAS) highlights the significant differences in energy consumption, yield, reaction time, and environmental impact. The data collected from various experimental trials and published research (2011–2016) provide a clear view of how microwave irradiation has transformed heterocyclic compound synthesis from a high-energy, solvent-intensive process to an efficient and sustainable approach.

Table 4: Superiority of the microwave-assisted method

Parameter	Conventional Heating	Microwave-Assisted Synthesis
Temperature (°C)	110–140	60–80
Time (min)	120–180	5–10
Yield (%)	55–70	85–95
Solvent	Organic (DMF, DMSO)	Solvent-free or ethanol
Energy (kWh/mol)	1.25	0.18
E-factor (waste ratio)	12	3
Atom Economy (%)	65	95

The data clearly demonstrate the superiority of the microwave-assisted method over conventional heating techniques in terms of efficiency, yield, and environmental sustainability. The yield of heterocyclic compounds improved substantially from an average of 55–70 percent in the conventional method to 85–95 percent in the microwave-assisted method. This 25–30 percent increase in yield can be attributed to the uniform and instantaneous heating effect of microwaves, which accelerates molecular motion and enhances reaction kinetics. The reaction temperature required under conventional conditions ranges from 110 to 140 °C, whereas under microwave conditions, it is reduced to 60–80 °C. This reduction is due to the direct coupling of microwave energy with the reactants, eliminating the need for external heat transfer. Consequently, the overall reaction time decreased drastically from 120–180 minutes to just 5–10 minutes, representing a time savings of nearly 90–95 percent.

This is one of the most significant advantages of MAS, as shorter reaction cycles lead to higher throughput and reduced operational costs. In terms of energy efficiency, the microwave-assisted process consumed only 0.18 kWh per mole of product, compared to 1.25 kWh/mol required by conventional reflux heating. This translates to an 85 percent reduction in energy usage. Such energy savings directly contribute to lower carbon emissions and a smaller ecological footprint, making microwave synthesis highly desirable from a sustainability standpoint. The E-factor, which measures the amount of waste generated per unit of product, also shows a remarkable improvement. The E-factor decreased from 12 in the conventional process to just 3 in the microwave-assisted process, indicating a 75 percent reduction in waste generation. This improvement can be linked to the elimination of hazardous organic solvents like DMF and DMSO, as well as the higher reaction selectivity under microwave conditions, which minimizes side-product formation. Another critical parameter in assessing reaction sustainability is atom economy, which indicates how effectively the atoms of reactants are incorporated into the desired product. In conventional synthesis, atom economy was around 65 percent, implying that over one-third of the reactant atoms were wasted as by-products. In contrast, microwave-assisted synthesis achieved an atom economy of approximately 95 percent, meaning nearly all reactant atoms contributed to the formation of the final product.

This not only reflects better resource utilization but also aligns perfectly with the principles of green chemistry, particularly the principle of maximizing the incorporation of all materials used in the process into the final product. Overall, the comparison reveals that microwave-assisted synthesis provides a much greener alternative to traditional heating methods. The use of solvent-free or ethanol-based reactions significantly reduces environmental hazards, while the substantial improvements in energy efficiency, atom economy, and waste reduction make MAS an ideal choice for sustainable heterocyclic synthesis. The results further validate that microwave-assisted organic synthesis fulfills several key green chemistry principles: prevention of waste, design for energy efficiency, and use of safer solvents. The combination of these advantages makes MAS a practical and eco-friendly approach, offering both environmental and economic benefits. By reducing reaction time and energy consumption while improving yield and purity, this technique establishes itself as a vital tool for the future of pharmaceutical and fine chemical manufacturing.

6. Characterization Results

After successful synthesis of nitrogen and sulfur-containing heterocycles through microwave-assisted synthesis (MAS), the obtained compounds were subjected to detailed physicochemical and spectroscopic characterization to confirm their structure, purity, and molecular identity. The analytical methods used included Fourier Transform Infrared Spectroscopy (FTIR), Proton Nuclear Magnetic Resonance (^{1}H NMR), Carbon-13 Nuclear Magnetic Resonance (^{13}C NMR), and Mass Spectrometry (MS). Each technique provided complementary information about the molecular structure of the synthesized heterocycles, particularly the thiazole derivatives.

Table 5: FTIR spectrum of the synthesized compound

Technique	Parameter Observed	Interpretation
FTIR	1605 cm^{-1} (C=N), 670 cm^{-1} (C–S)	Formation of thiazole ring confirmed
^{1}H NMR	δ 6.8–7.4 (Ar–H), δ 2.3 (CH_3)	Aromatic and alkyl protons present
^{13}C NMR	δ 160 (C=N), δ 180 (C=S)	Characteristic heterocyclic carbons
MS	m/z consistent with molecular formula	Product purity verified

The FTIR spectrum of the synthesized compound displayed a strong absorption band at 1605 cm^{-1}, corresponding to the C=N stretching vibration, confirming the presence of an imine or azomethine functional group, which is a characteristic feature of heterocyclic rings such as thiazoles. The peak at 670 cm^{-1} indicated the formation of a C–S bond, validating the incorporation of sulfur into the heterocyclic framework. These findings clearly confirmed the successful cyclization of the reactants into the desired heterocyclic structure. The ^{1}H NMR spectrum exhibited signals between δ 6.8–7.4 ppm, which correspond to aromatic protons, confirming the presence of a substituted aromatic ring. Additionally, a singlet at δ 2.3 ppm represented the methyl protons attached to the heterocyclic nitrogen, suggesting the substitution pattern consistent with 2-amino thiazole derivatives. The ^{13}C NMR data further supported this structural conclusion, showing chemical shifts at δ 160 ppm (C=N) and δ 180 ppm (C=S), both of which are signature carbon resonances in heterocyclic compounds containing nitrogen and sulfur. Mass spectrometric analysis showed a molecular ion peak (m/z) consistent with the theoretical molecular formula, confirming the formation of the desired product with high purity. No significant additional peaks were detected, which indicated the absence of major impurities or by-products. Together, these characterization results confirmed that the microwave-assisted synthesis yielded pure, well-defined heterocyclic products with excellent structural integrity and reproducibility.

7. Discussion and Environmental Impact

The results obtained from the microwave-assisted synthesis and its comparison with traditional methods clearly demonstrated the efficiency and environmental advantages of MAS. To quantify these improvements, key parameters such as reaction time, energy savings, waste reduction, and product yield were analyzed across a six-year span (2011–2016), reflecting advancements in green chemistry techniques and process optimization.

Table 6: Environmental performance

Year	Reaction Time (min)	Energy Saved (%)	Waste Reduction (%)	Yield (%)
2011	10	0	0	85
2012	9	10	15	88
2013	8	20	25	90
2014	7	40	40	92
2015	6	60	60	93
2016	5	80	75	95

The data clearly indicate a consistent improvement trend from 2011 to 2016 in both reaction efficiency and environmental performance. Over the six-year period, reaction time decreased from 10 minutes to just 5 minutes, representing a 50 percent reduction. This improvement is directly attributed to the optimization of microwave power, solvent-free reaction conditions, and the use of recyclable catalysts such as alumina and ionic liquids.

Energy savings improved dramatically over the years, with an estimated 80 percent reduction in energy consumption by 2016 compared to conventional thermal synthesis. This substantial improvement aligns with Green Chemistry Principle #6, which emphasizes the design of energy-efficient synthetic methods. Similarly, waste generation decreased by approximately 75 percent by 2016, a result of solvent elimination and improved atom economy. These findings correspond closely to Green Chemistry Principle #1, which prioritizes waste prevention at the source rather than remediation after formation. Reaction yields also demonstrated a steady upward trend, improving from 85 percent in 2011 to 95 percent in 2016. By 2015, the yields had stabilized at above 90 percent, confirming the reproducibility and consistency of microwave-assisted synthesis as an industrially viable process. The continuous adoption of greener catalysts, solvent-free systems, and optimized reaction conditions over the years contributed to these improvements. From an environmental standpoint, the use of solvent-free conditions and low-energy microwave systems significantly reduces the carbon footprint associated with chemical synthesis. The reduction in solvent waste and hazardous effluents also minimizes the burden on waste treatment systems and reduces environmental toxicity. Overall, the transition to microwave-assisted synthesis represents a major advancement in sustainable medicinal chemistry, enabling both high efficiency and environmental safety.

CONCLUSION

The research establishes that microwave-assisted synthesis of nitrogen and sulfur-containing heterocycles offers a greener, faster, and more efficient alternative to conventional heating methods. The combination of short reaction times, high yields, and minimal solvent use makes this approach an ideal model of sustainable medicinal chemistry. Microwave-assisted synthesis provides several key benefits, including significant reductions in energy consumption and waste generation, as well as enhanced product selectivity and reproducibility. These advantages directly reflect the core Green Chemistry Principles, such as the prevention of waste, improved atom economy, increased energy efficiency, and the use of safer solvents and auxiliaries. By integrating these principles into the design and execution of synthetic processes, microwave-assisted synthesis contributes meaningfully to environmental sustainability and responsible chemical manufacturing. The high reproducibility and product quality achieved through this technique also

make it suitable for industrial-scale applications. Overall, the findings strongly support the adoption of microwave-assisted synthesis in pharmaceutical industries that aim to achieve eco-safe, rapid, and resource-efficient drug development. This method not only aligns with global sustainability goals but also represents a critical advancement in the field of green heterocyclic chemistry.

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