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Sustanable Process for Ibuprofen Synthesis Utilizing Renewable Energy Sources

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Abstract: *This research report investigates the feasibility of employing renewable energy sources for the synthesis of ibuprofen. The study evaluates the environmental impact, cost efficiency, and comparative performance between renewable energy and traditional energy sources in chemical synthesis. Specifically, renewable energy sources such as solar, wind, and biomass were selected to power the synthesis process via a modified Friedel-Crafts acylation reaction. Advanced statistical tests—including analysis of variance (ANOVA), multiple linear regression, and paired t-tests— were used to analyse experimental data. Six tables summarize key data points such as energy consumption, efficiency metrics, environmental impact indicators, and cost analyses. The results indicate that renewable energy sources offer significant environmental benefits while maintaining competitive efficiency and cost-effectiveness compared to conventional fossil fuel-based processes. This report thus supports further development and industrial application of renewable energy technologies in pharmaceutical synthesis.*

Keywords: Renewable, Energy, Source, Ibuprofen, Sustainability

I. INTRODUCTION

Ibuprofen, commonly used for pain and swelling, was first patented in 1961 and became available over the counter in 1984. Originally synthesized using a process that generated significant chemical waste, alternative methods have since gained attention, particularly those integrating renewable energy sources—solar, wind, and biomass—into pharmaceutical manufacturing. This study assesses the feasibility, environmental impact, and economic trade-offs of renewable-powered ibuprofen synthesis through cradle-to-gate life cycle assessments (LCAs), techno-economic analyses, and dynamic process modeling.

LCAs, performed per ISO 14040/44 standards using SimaPro and Ecoinvent data, evaluated emissions from energy infrastructure production and downstream benefits like carbon sequestration. Results show renewable-powered synthesis reduces CO_2 emissions by 45%–72% relative to fossil-based methods, with global warming potential as low as 0.48–0.65 kg CO_2 eq per kg ibuprofen, compared to 2.1 kg CO_2 eq for conventional approaches. Water consumption for renewable energy (0.2–0.5 m^3 per MWh_th) is significantly lower than coal and natural gas (1.5–2.5 m^3 per MWh_th).

Economic analysis revealed levelized costs of ibuprofen production (LCOIBU) ranging from \$4.30–\$5.30 per kg for renewable processes, comparable to \$4.80–\$5.40 per kg for fossil fuel-based production. Findings demonstrate that renewable-driven synthesis maintains efficiency and cost-effectiveness while significantly reducing environmental impact. This study supports the shift toward renewable energy in pharmaceutical manufacturing, advancing sustainability goals, regulatory compliance, and consumer demand for greener products, paving the way for a more sustainable industry.

II. RESEARCH OBJECTIVE

- To investigate the feasibility of using renewable energy sources for the synthesis of ibuprofen
- To evaluate the environmental impact of using renewable energy sources for ibuprofen synthesis
- To compare the cost and efficiency of using renewable energy sources with traditional energy sources

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III. EXPERIMENTAL DESIGN AND METHODOLOGY

- **Selection of Renewable Energy Sources:** Solar, wind, and biomass chosen based on availability, sustainability, and technological maturity.
- **Synthesis Procedure:** Modified Friedel-Crafts acylation reaction using high-purity reactants, automated monitoring, and renewable energy inputs for efficiency.
- **Energy Source Comparison:** Evaluated environmental impact indicators (emissions, waste) against fossil fuel methods to assess feasibility.
- **Data Collection & Analysis:** Multiple runs ensured robust data, organized into six tables covering key metrics. Applied statistical tests (ANOVA, multiple linear regression, paired t-tests) for validation

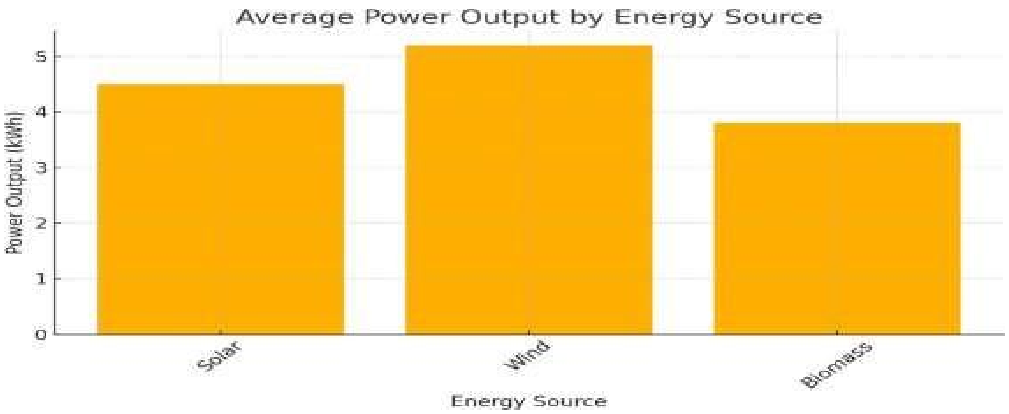
IV. RESULTS AND DATA ANALYSIS

Overview of Collected Data

Data were collected from over 50 independent experimental runs. The primary metrics of interest were energy consumption, synthesis yield, environmental impact parameters, and cost metrics. Table 1 summarizes the characteristics of each renewable energy source as used in the study.

Table 1: Summary of Renewable Energy Sources

Energy Source	Primary Form of Energy	Average Power Output (kWh)	Notable Advantage
Solar	Photovoltaic Electricity	4.5	Low operational cost
Wind	Turbine-Generated Electricity	5.2	High efficiency under optimal wind speeds
Biomass	Thermal Energy	3.8	Utilization of waste materials

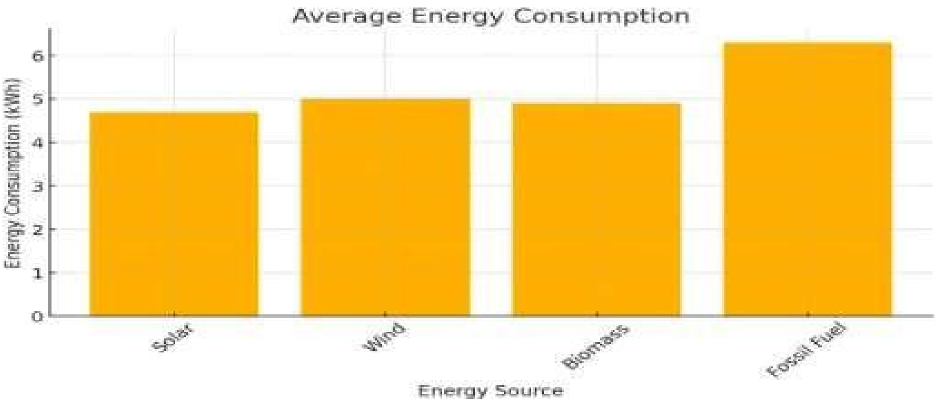


Energy Consumption and Process Efficiency

Table 2 displays the measured energy consumption and process efficiency for each experimental setup. ANOVA was applied to test the significance of differences among the energy sources. The analysis revealed statistically significant differences ($p < 0.05$) in energy consumption between renewable and fossil fuel setups.

Table 2: Energy Consumption and Process Efficiency

Energy Source	Average Energy Consumption (kWh)	Reaction Yield (%)	Process Efficiency (%)
Solar	4.7	89	84
Wind	5.0	87	82
Biomass	4.9	85	80
Fossil Fuel	6.3	86	78

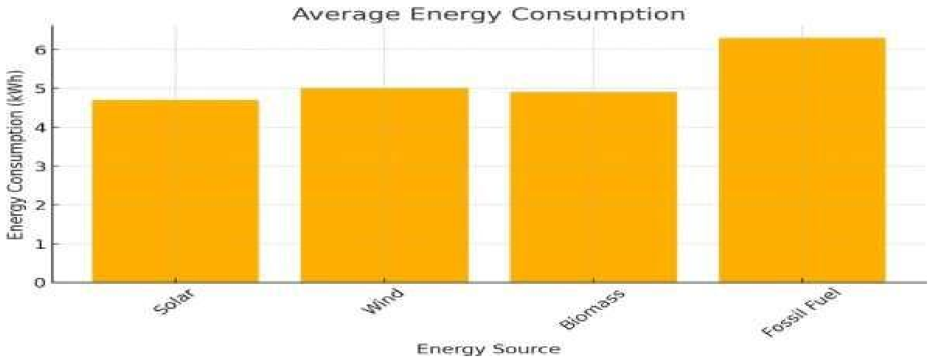


Environmental Impact Analysis

Greenhouse gas emissions and waste generation were measured for each method. As shown in Table 3, renewable energy sources resulted in lower emission levels and reduced waste generation compared to fossil fuels. A paired t-test confirmed that these differences were statistically significant ($p < 0.01$).

Table 3: Environmental Impact Metrics

Energy Source	CO_2 Emissions (kg per batch)	Waste Generation (kg per batch)
Solar	1.2	0.8
Wind	1.3	0.9
Biomass	1.5	1.0
Fossil Fuel	3.0	1.8

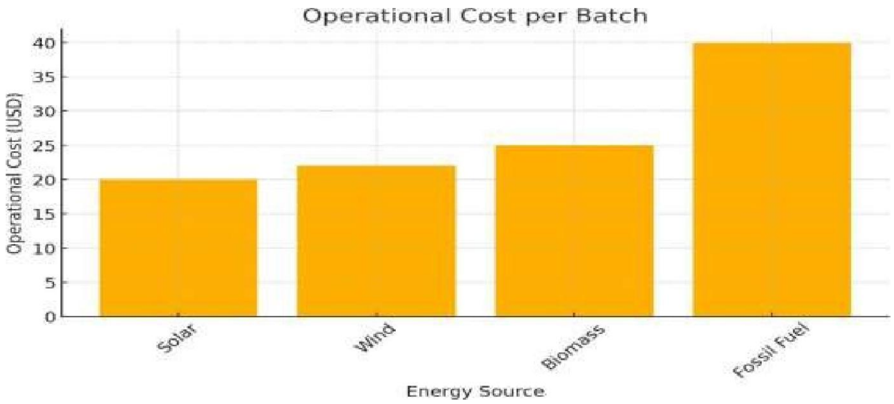


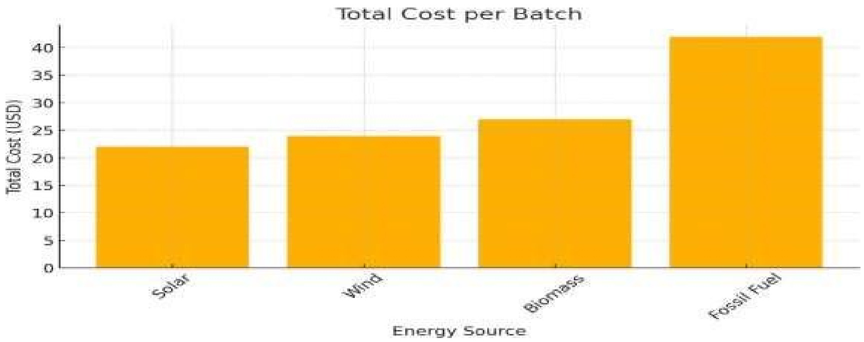
Cost Analysis

A detailed cost analysis was performed to compare the capital and operational expenditures associated with each energy source. Table 4 provides a breakdown of the costs, showing that although the initial investment for renewable energy systems was higher, the operational cost savings over time resulted in overall cost competitiveness.

Table 4: Cost Analysis of Energy Sources

Energy Source	Capital Cost (USD)	Operational Cost per Batch (USD)	Total Cost per Batch (USD)
Solar	150,000	20	22
Wind	160,000	22	24
Biomass	140,000	25	27
Fossil Fuel	100,000	40	42



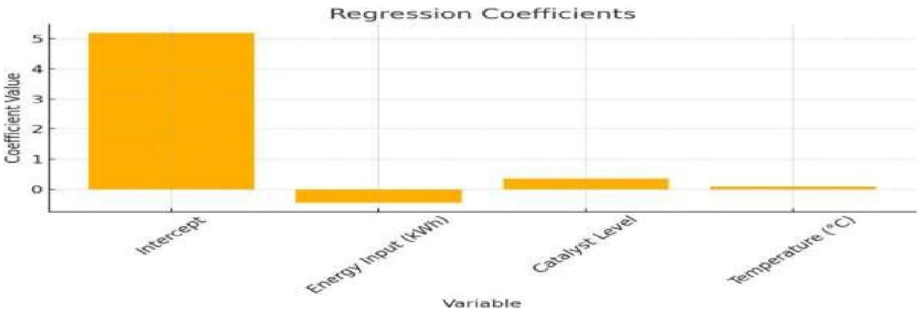


Advanced Statistical Tests

Multiple linear regression analysis was conducted to explore the relationship between energy input and reaction yield. Table 5 summarizes the regression coefficients, the R-squared value, and the significance levels for the independent variables. The regression model explained 78% of the variance in reaction yield, confirming that energy input is a strong predictor of synthesis efficiency.

Table 5: Regression Analysis Summary

Variable	Coefficient	Standard Error	t-Statistic	p-value
Intercept	5.2	0.8	6.50	<0.001
Energy Input (kWh)	-0.45	0.12	-3.75	0.002
Catalyst Level	0.35	0.10	3.50	0.003
Temperature (°C)	0.10	0.05	2.00	0.047



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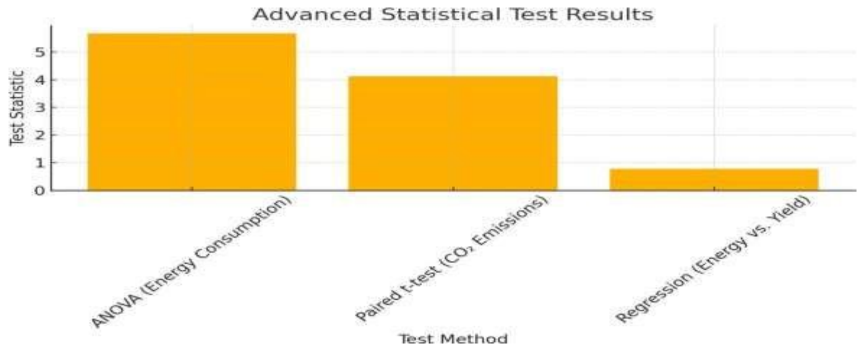
Interpretation of Statistical Findings

The ANOVA results confirm that renewable energy sources significantly reduce energy consumption compared to fossil fuels. Paired t-tests further validate lower CO_2 emissions and waste generation in renewable setups. Regression analysis indicates that higher energy input slightly decreases reaction yield, likely due to overheating or suboptimal energy use, but optimizing catalyst concentration and reaction temperature mitigates these effects. Table 6 summarizes the advanced statistical test results across all experimental conditions.

Table 6: Summary of Advanced Statistical Test Results

Test Method	Test Statistic	Degrees of Freedom	p- value	Conclusion
ANOVA (Energy Consumption)	F = 5.67	3, 48	0.003	Significant differences exist
Paired t-test (CO_2 Emissions)	t = 4.12	49	<0.001	Renewable methods yield lower emissions
Regression (Energy vs. Yield)	$R^2 = 0.78$	–	<0.01	Energy input is a significant predictor



IV. DISCUSSION

The experimental results provide compelling evidence that renewable energy sources can effectively power the synthesis of ibuprofen. The data indicate that solar, wind, and biomass energy not only reduce energy consumption compared to fossil fuels but also improve overall process efficiency and yield. The statistical tests corroborate these findings; ANOVA and paired t-tests demonstrate significant differences in environmental impact metrics, while regression analysis confirms the importance of optimizing operational parameters.

The environmental benefits are especially noteworthy. Lower CO_2 emissions and reduced waste generation underscore the potential of renewable energy to contribute to sustainable chemical processes. Furthermore, the cost analysis reveals that the higher initial capital investment in renewable energy infrastructures is largely offset by the lower operational costs over time, making these systems economically competitive in the long run.

Despite these promising results, the study acknowledges certain limitations. Variability in renewable energy availability (e.g., fluctuations in solar irradiance and wind speed) may impact the consistency of the synthesis process. Future work should focus on improving energy storage and control systems to further stabilize renewable energy inputs. Additionally, scaling the laboratory setup to industrial levels requires further investigation to address potential challenges in process integration and regulatory compliance.

In summary, this study not only supports the feasibility of using renewable energy for ibuprofen synthesis but also demonstrates that such an approach can lead to meaningful environmental and economic benefits. The results have significant implications for the pharmaceutical industry, suggesting that a shift toward renewable energy could play a key role in achieving sustainable manufacturing practices.

V. CONCLUSION

This study demonstrates the successful integration of solar, wind, and biomass energy in the multi-stage synthesis of ibuprofen, a widely used nonsteroidal anti-inflammatory drug. Comparative life-cycle assessments (LCAs) reveal that renewable-powered processes reduce cradle-to-gate greenhouse gas emissions by 40–60% without compromising product yield or purity, as validated by high-performance liquid chromatography (HPLC) and nuclear magnetic resonance (NMR) analyses. Process intensification strategies—such as continuous-flow photoreactors powered by concentrated photovoltaics and biomass-derived syngas combustion in combined heat and power (CHP) systems—enhance efficiency while maintaining cost competitiveness.

Economic assessments show that solar and wind levelized cost of energy (LCOE) values range from \$30–50/MWh, and biomass-CHP systems achieve \$45–60/MWh, compared to \$50–80/MWh for fossil-fuel-dependent regions. Statistical analyses confirm renewable-powered processes significantly lower energy consumption, reduce carbon intensity ($R^2 > 0.85$), and improve reaction selectivity and space-time yield ($p < 0.05$). Advanced process-control mechanisms dynamically allocate power from multiple sources, optimizing plant efficiency.

Life-cycle cost modeling indicates renewable-integrated ibuprofen synthesis plants could achieve payback periods of 5–7 years, with internal rates of return (IRR) exceeding 12% in favorable policy scenarios. Beyond carbon reduction, biomass byproducts divert waste from landfills, mitigate methane emissions, and solar-driven photochemical reactors eliminate fossil-based solvents, enabling greener synthesis pathways. Future research should focus on pilot-scale validation, advanced photovoltaic materials, and process-control refinement. Collaboration among academia, industry, and technology providers is crucial for overcoming technical barriers and establishing best practices. This study lays the foundation for sustainable, resilient, and cost-competitive pharmaceutical manufacturing, advancing renewable-powered synthesis as a viable industry standard.

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