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Process Optimization and Environmental Analysis of Ultrasound-Assisted Biodiesel Production from *Pangasius* Fat Using $CoFe_2O_4$ Catalyst

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ABSTRACT: This study optimized biodiesel synthesis from Pangasius fat using a Box-Behnken experimental design. The manipulation of key variables included the $CoFe_2O_4$ catalyst dosage, the methanol-to-fat molar ratio, and the ultrasonic wave amplitude. We determined optimal conditions for biodiesel synthesis through the central runs, resulting in a remarkable 96.5% yield. The produced biodiesel exhibited diverse fatty acid compositions and met specifications for viscosity, specific gravity, acid value, and iodine value. Furthermore, we conducted a comprehensive life cycle assessment (LCA) to shed light on the environmental implications of the process. The LCA revealed a minimal global warming potential of 0.21 kg CO_2 per kg of biodiesel produced, demonstrating the environmental viability of the entire process. These significant findings highlight the promising potential of using *Pangasius* fat as a sustainable feedstock for biodiesel production. Additionally, they provide valuable insights into developing ecologically friendly energy sources.

INTRODUCTION

Annually, the Mekong Delta region generates around 1.5 million tons of *Pangasius*, resulting in approximately 800,000 tons of byproducts, including heads, skin, bones, and fats.[1] Among these byproducts, there is potential to extract roughly 150,000 tons of fish oil, half refined into cooking oil. However, unused fish oil holds significant value for animal feed and biodiesel production, and neglecting its utilization contributes to waste and pollution.[2]

The economic viability of *Pangasius* byproducts makes them attractive for incorporation into animal feed. However, there remains untapped potential in transforming these materials into biodiesel. Earlier studies[3] have highlighted the richness of *Pangasius* fat (PF) in saturated fatty acids, notably palmitic and stearic acids, which comprise around 39% of its composition. This distinct composition positions PF as a highly suitable candidate for biodiesel production, underscoring its inherent promise. Such utilization not only aids in curbing environmental pollution but also provides a sustainable alternative to fossil fuels, effectively repurposing resources that would otherwise be discarded.

Conventional biodiesel synthesis has traditionally relied upon homogeneous catalysts such as KOH, NaOH, H_2SO_4, CH_3ONa, etc., often employing alkaline or acidic agents.[3] However, the intricate separation and recovery procedures of these catalysts have led to energy-intensive processes, escalating production costs, and environmental concerns. In response, the design and implementation of magnetic catalysts for biodiesel production have garnered considerable attention.[4] These catalysts enable efficient mixing and reaction control by functionalized magnetic nanoparticles with appropriate catalytic moieties. In contrast, external magnetic fields facilitate easy recovery, eliminating the need for energy-intensive separation methods. The focus on innovative catalysts and processes to enhance sustainable biodiesel production has grown.[5] A particularly promising avenue involves the integration of magnetic catalysts and ultrasonic techniques, aiming to enhance reaction kinetics and overall yield.[6] Concurrently, ultrasonic methodologies have emerged as effective tools for intensifying the biodiesel production processes. They facilitate efficient emulsification, improve mass transfer, and enhance transesterification reactions. The convergence of these advancements has the potential to reshape biodiesel production, making it not only more sustainable but also economically feasible.[4]

Simultaneously, ultrasonic technology has shown substantial promise in intensifying biodiesel production processes. Using ultrasound, which can induce cavitation-driven mechanical and chemical effects, aids in better dispersion of reactants and helps break down mass transfer obstacles, thus accelerating reaction rates.[7] Integrating ultrasound into biodiesel synthesis has been observed to increase yield, shorter reaction times, and lower

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energy usage, aligning perfectly with the goals of sustainable and efficient biodiesel production.[8]

However, the concurrent application of magnetic catalysts and ultrasonic methodologies is a relatively unexplored path in biodiesel synthesis. The potential synergy between these techniques holds the prospect of magnifying their advantages, thus presenting an innovative avenue for enhancing biodiesel production efficiency, yield, and overall sustainability.

However, the traditional biodiesel production approach involves transesterifying triglycerides or fatty acids with alcohol, utilizing homogeneous catalysts. This method is known for its resource-intensive nature, leading to increased production costs.[9] The conventional technique often faces challenges such as slow reaction rates and difficulties in blending immiscible phases of fatty acids and alcohol. This results in a mixture of fatty acid methyl esters and glycerol. Furthermore, recovering or recycling the catalysts from the reaction mixture presents complications.[10] Researchers have explored novel paths involving heterogeneous catalysts and innovative strategies to overcome these limitations. One promising route involves the combined application of ultrasound and heterogeneous catalysts for biodiesel synthesis, a methodology that has demonstrated the ability to enhance reaction efficiency and catalyst reusability.

While numerous studies have successfully combined ultrasound technology with heterogeneous catalysts for biodiesel production,[11] a research gap remains related to optimizing crucial factors and understanding environmental implications. Addressing these dimensions is vital for the practical implementation of biodiesel synthesis and requires further exploration to bridge the existing knowledge gap.

Although our initial investigation[3] explored biodiesel synthesis from PF using a Taguchi design, ultrasound technology, and a KOH catalyst, we encountered certain challenges. The presence of KOH contamination in the biodiesel and the incomplete regression between parameters limited the overall contribution of our study. While our research provided valuable insights, there remains room for improvement in the PF-derived biodiesel synthesis.

Building upon previous research, the present study aims to optimize biodiesel production from PF through a Box-Behnken design. This approach encompasses three variables: the concentration of $CoFe_2O_4$ (a heterogeneous magnetic catalyst), the molar ratio of MeOH to PF, and the amplitude of ultrasonic waves. Moreover, this inquiry integrates a preliminary life cycle assessment (LCA) to assess the environmental impact of laboratory-scale biodiesel production from PF. Importantly, the utilization of magnetic $CoFe_2O_4$ in ultrasound-assisted biodiesel production from PF has not been extensively explored in prior studies.

EXPERIMENTAL SECTION

Materials. The PF used in this study was sourced from a factory located in South Vietnam, while the $CoFe_2O_4$ catalysts were synthesized using the polyethylene glycol-assisted sol−gel method. More detailed information about these compounds has been reported.[3,12] The chemicals utilized in this study, such as methanol (90%), dichloromethane (≥99%), and hexane (anhydrous, ≥99%), among others, were obtained from Sigma-Aldrich (USA).

Transesterification Process. The ultrasonic-assisted reaction was performed using a Sonics ultrasonic horn (United States), operating at 20 kHz and power dissipation of 750 W, as detailed in our previous study.[3] The reactor was filled to one-third of its capacity with distilled water, and a pump-operated thermostated bath maintained the temperature at 50 ± 2 °C. A specific volume of PF along with a predetermined amount of catalyst and methanol was added to the reactor. The ultrasonic amplitude and reaction time were adjusted for each experiment using a personal computer (PC) controller, following the principles of the Box-Behnken method. The resulting heterogeneous mixture, comprising biodiesel, glycerol, and catalyst, was then collected in a separation funnel, allowing for oil extraction at predetermined intervals. The obtained oil layer was subjected to a hot water rinse to remove contaminants. Excess methanol and water were evaporated using a microwave oven (MS 622 BIS L, Teka Group, Germany) before chromatographic analysis (6890N Agilent FID-GC, USA). To ensure the accuracy of the results and account for potential errors, various biodiesel parameters, including kinematic viscosity, specific gravity, acid value, and iodine value, were investigated following the standards outlined by EN or ASTM, as indicated in a previous study.[13]

Experiment Design. The study employed a Box-Behnken design to investigate the effects of three parameters: the amount of the $CoFe_2O_4$ catalyst, molar ratio of MeOH to fat, and ultrasonic amplitude on the conversion of triglycerides into biodiesel. The experimental investigation involved three levels: low (−1), intermediate (0), and high (+1). Based on a preliminary experiment, these factors, designated as *A*, *B*, and *C*, were identified as significant in the multiplication process of bacterial biomass. The details of the factors and their levels are presented in Table 1.

Table 1. Three Levels of the Process Parameters

	coded levels		
factors	−1	0	+1
$CoFe_2O_4$ amount - X_1 (g)	0.5	1.0	1.5
MeOH/fat - X_2	4:1	5:1	6:1
ultrasonic amplitude - X_3 (%)	60	80	100

The regression model can be expressed as eq 1:

$$Y = b_0 + b_1A + b_2B + b_3C + b_{12}AB + b_{13}AC + b_{23}BC + b_{11}A^2 + b_{22}B^2 + b_{33}C^2 \quad (1)$$

In this equation, b_0 represents the regression coefficient at the center, while b_1, b_2, and b_3 represent the linear coefficients. The interaction coefficients are denoted by b_{12}, b_{13}, and b_{23}. Moreover, the quadratic coefficients are represented by b_{11}, b_{22}, and b_{33}.

Life Cycle Assessment (LCA). LCA is a widely used methodology to assess environmental impacts associated with the production of products. It involves four phases: establishing scope and objectives, inventory compilation, impact assessment, and interpretation of results.[14] In this study, the analysis focuses on a "gate-to-gate" perspective, specifically examining the manufacturing phase of the cobalt ferrite catalyst, which is produced using the sol−gel method with the support of polyethylene glycol (PEG). The data used in the assessment are sourced from previous studies.[12] The production process of biofuel from fish oil using the ultrasonic method resulted in a biodiesel efficiency rate of 97.3%. The data for this specific segment were procured from the ecoinvent 3.8 database (https://v391.ecoquery.ecoinvent.org/

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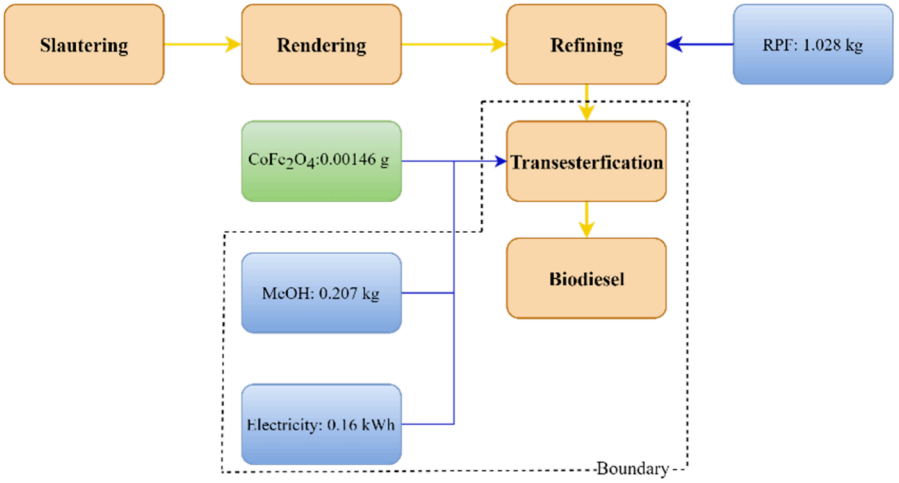

Figure 1. Delimitation of boundaries for the biodiesel production process and inventory analysis (illustrating process components with orange, own synthesis products with green, and purchased products with blue boxes, displaying the process flow with an orange line and process inputs with a blue line).

). However, it is important to note that this analysis did not include certain processes, including fish oil procurement, biodiesel utilization, and the byproducts generated during biodiesel production. The individual unit processes associated with these aspects are represented in Figure 1.

The assessment of the environmental impact of the biodiesel production process from fish fat focuses on producing 1 kg of biodiesel. The ReCiPe V1.13 midpoint H and end point H methods, available in the SimaPro9.5 software, were employed for this evaluation. These assessment methodologies were developed in collaboration with institutions such as the National Institute for Public Health and the Environment (RIVM), the Institute of Environmental Sciences (CML), PRé Consultants, and Radboud University Nijmegen and are widely used in life cycle analyses.[4] It is important to note that the evaluations and findings are specific to laboratory-scale processes.

RESULTS AND DISCUSSION

Model Fitting and Validation. The Box-Behnken experimental design model was utilized in this study, incorporating three variables with three levels each to optimize the biodiesel synthesis process from Pangasius adipose tissue, as displayed in Table 2. The results analysis revealed that the central runs (13th to 15th) demonstrated a higher efficiency in biodiesel synthesis than the other runs. The 14th run, particularly noteworthy, achieved a biodiesel yield of 95.35%, indicating its superior performance. The study also revealed a minor discrepancy between the experimental results and the models' predictions regarding biodiesel synthesis efficiency.

The model equation was subjected to statistical validation to assess its accuracy and reliability. This validation included evaluating the correlation coefficient (R^2), performing analysis of variance (ANOVA) using the *F*-test and examining the p-value. The *p*-value is a statistical tool that helps analyze the different sources of variation within a data set. In this case, the low *p*-value (0.000 < 0.01) indicates the statistical significance of the model. Furthermore, the high *F*-value of 343.54 suggests that the regression equation effectively explains a substantial portion of the variation. These statistical results are summarized in Table 3. The model's reliability was further validated by a high R^2 value of 0.9984, indicating a strong

Table 2. Box-Behnken Design with Experimental and Predicted Values

	factors			biodiesel yield (%)	
	A	*B*	*C*	experimental	predicted
1	0.5	4	80	62.75	62.15
2	1.5	4	80	66.71	66.46
3	0.5	6	80	70.84	71.09
4	1.5	6	80	87.86	88.46
5	0.5	5	60	65.91	66.01
6	1.5	5	60	73.89	73.63
7	0.5	5	100	67.19	67.45
8	1.5	5	100	81.6	81.51
9	1	4	60	65.82	66.33
10	1	6	60	78.16	77.82
11	1	4	100	66.66	67.00
12	1	6	100	86.96	86.45
13	1	5	80	93.67	94.58
14	1	5	80	95.35	94.58
15	1	5	80	94.73	94.58

Table 3. Analysis of Variance (ANOVA) for PF Biodiesel Production[a]

terms	DF	adj SS	adj MS	*F*-value	*P*-value
model	9	1972.48	219.164	343.54	0.000
A	1	235.12	235.120	368.55	0.000
B	1	478.64	478.642	750.27	0.000
C	1	43.38	43.385	68.01	0.000
A^2	1	567.54	567.538	889.62	0.000
B^2	1	380.05	380.047	595.72	0.000
C^2	1	372.04	372.036	583.17	0.000
AB	1	42.64	42.641	66.84	0.000
AC	1	10.34	10.336	16.20	0.010
BC	1	15.84	15.840	24.83	0.004
residual error	5	3.19	0.638		
lack of fit	3	1.75	0.582	0.81	0.595
pure error	2	1.44	0.722		
total	14	1975.67			

[a] R^2 = 0.9984 and R^2_{adj} = 0.9955.

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correlation between the predicted and experimental results. The lack of fit p-value (0.810 > 0.01) also suggests that the model adequately represents the experimental range. It is worth noting that all factors listed in Table 3, including linear absorbed doses (A, B, C), squares (A^2, B^2, and C^2), and interactions (AB, AC, and BC), were found to be significant in the model. The hierarchical relationship between these variables is visually depicted in Figure 2. The responses

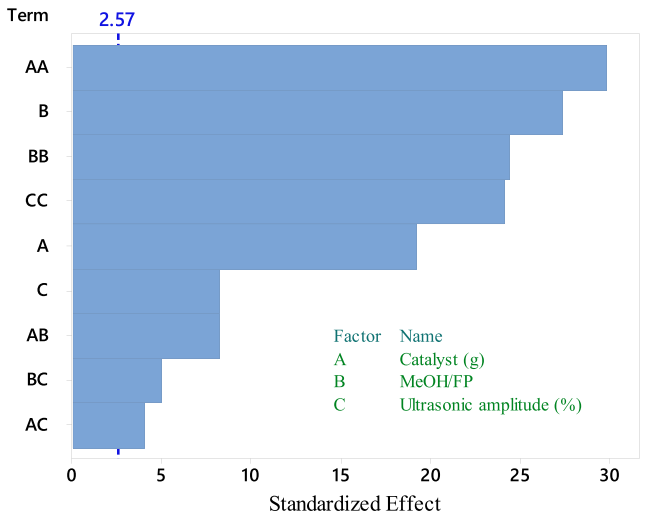


Figure 2. Pareto chart showing levels of important factors in biodiesel conversion.

obtained for biodiesel synthesis from PF were fitted into a second-order polynomial equation expressed in eq 2.

$$Y = -342.8 + 64.52A + 94.70B + 3.473C - 49.59A^2 - 10.145B^2 - 0.02509C^2 + 6.530AB + 0.1607AC + 0.0995BC \quad (2)$$

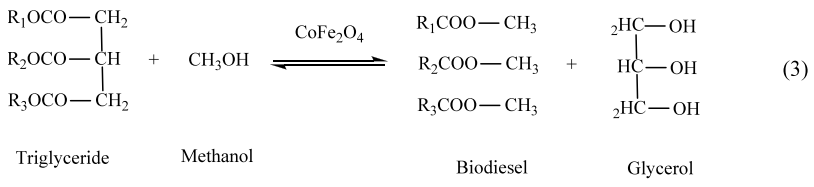
Upon close examination of the normal probability plot (Figure 3a) within the context of biodiesel production, it is evident that the data points exhibit a commendable alignment with a linear pattern. This alignment substantiates the normal distribution of residuals, a foundational principle that underpins the reliability of the applied statistical tests. Importantly, the consistent alignment of data points along a linear trajectory enhances the model's ability to capture the inherent variability within the biodiesel production process effectively. Deviation from this linear alignment would warrant further investigation of the normality assumption, potentially prompting the exploration of alternative models or transformative techniques. The alignment between our findings and the anticipated norms of normality reinforces the validity of our statistical analyses in the specific realm of biodiesel production optimization.

Directing our attention to Figure 3b, depicting the scatter of residuals against fitted values, we gain insights into the uniformity of residual variance, particularly within biodiesel production. The conspicuously random distribution of residuals across varying levels of fitted values accentuates the consistent variance of the residuals, a phenomenon known as homoscedasticity. The implications of homoscedasticity extend beyond conventional statistical models, finding particular resonance in biodiesel production optimization models. The absence of discernible patterns within this scatter plot is evidence of the homoscedasticity assumption being met, reinforcing the accuracy of our model's predictions and conclusions. Importantly, it is worth emphasizing that any noticeable patterns within this scatter plot could indicate heteroscedasticity, a phenomenon capable of introducing bias to standard errors and undermining the integrity of the model's inferences.

A compelling correlation becomes evident on comparing our findings with the seminal contributions of Neag et al.[15] and the insightful research by Hadrich et al.[16] This correlation emphasizes a mutual acknowledgment of the crucial significance attributed to the assumptions of normality and homoscedasticity. These assumptions safeguard the reliability and validity of statistical analyses in the complex landscape of biodiesel production.

Effect of Process Parameters. Figure 4a–c presents contour plots illustrating the relationship between catalyst dosage, MeOH/PF ratio, ultrasonic amplitude, and the resulting biodiesel yield. One notable observation from this analysis is the significant impact of the square of the catalyst amount and MeOH/PF ratio on the biodiesel yield. These factors exhibit a synergistic interaction that influences the synthesis process. Examining Figure 4a,b, it is evident that there is a gradual increase in biodiesel yield as the MeOH/RPF molar ratio increases from 4:1 to 6:1. This ratio plays a crucial role in driving the conversion of oil during transesterification. Its optimization is essential for achieving higher biodiesel yields. The theoretical model suggests a stoichiometric ratio of one mole of oil to three moles of alcohol (MeOH) for biodiesel synthesis, as indicated in eq 3. However, using an excess volume of MeOH in practice is common. This excess of MeOH helps shift the reaction equilibrium toward biodiesel synthesis, resulting in higher yields.[17] Nevertheless, when the MeOH/PF ratio reaches 6:1, there is a slight decrease in the biodiesel yield. This decrease may be attributed to a reverse reaction occurring when the availability of RPF molecules becomes limited and the solubility of glycerol increases in the ester phase. These factors can compromise biodiesel quality.[18]

The trend observed in catalysis aligns with the findings in Figure 4a,c, which demonstrate an accelerated transesterification rate as the catalyst concentration increases. However, it is important to note that low catalyst concentrations, particularly below 1.2 g of $CoFe_2O_4$, lead to a suboptimal biodiesel yield. On the other hand, a catalyst concentration exceeding 1.2 g can potentially induce a saponification reaction, which has a negative impact on biodiesel yield. This phenomenon can be attributed to the enhanced adsorption of MeOH and PF on the catalyst surface at the optimal concentration, thereby promoting the reaction between these compounds to produce



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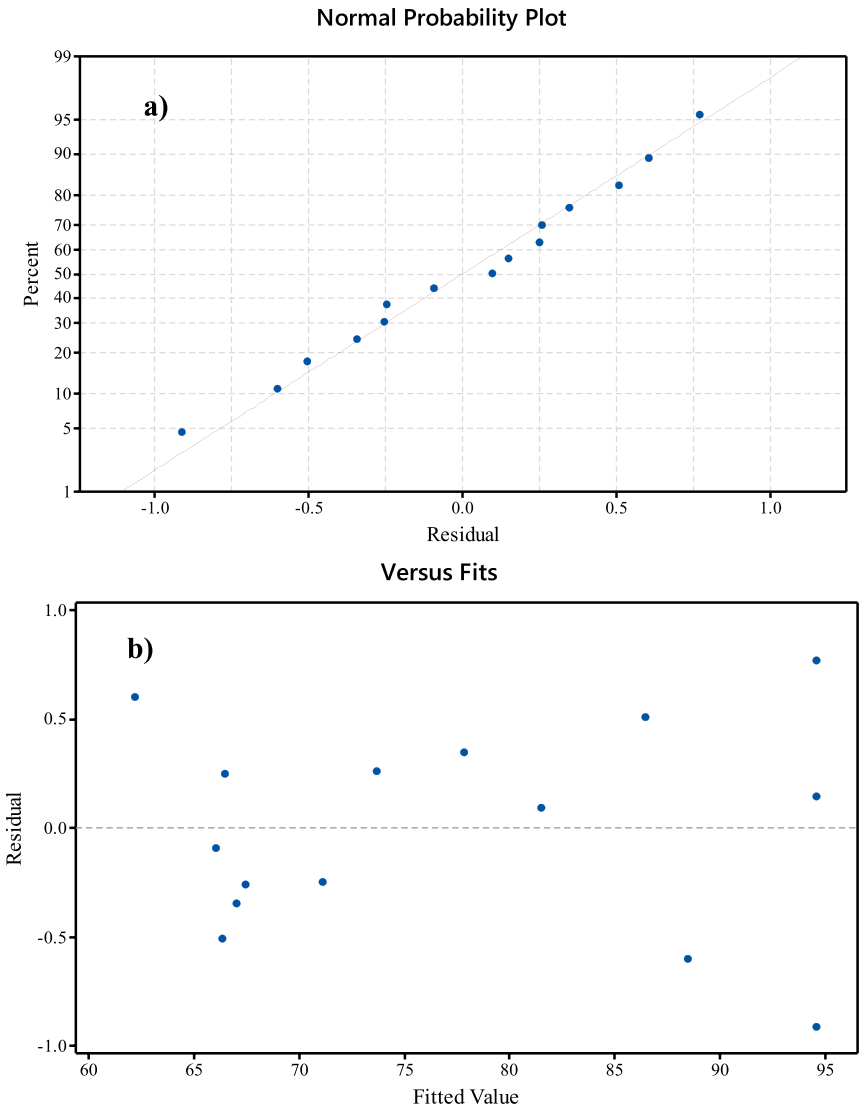

Figure 3. Residual analysis graphs: (a) probability plot and (b) residuals vs fitted values.

a fatty acid ester and glycerol. This hypothesis is supported by a study conducted by Pasupulety et al.,[19] who investigated the use of Al_2O_3 catalysts in the extraction of biodiesel from soybean oil.

The manipulation of ultrasonic amplitudes also plays a significant role in biodiesel production, as evidenced in Figure 4b,c. The rate of biodiesel conversion shows a positive correlation with an increasing ultrasonic amplitude up to a threshold of 85%. However, beyond this threshold, the conversion rate starts to decrease. This trend can be attributed to the enhanced homogenization of PF, methanol, and catalyst blend through acoustic cavitation facilitated by ultrasound. Acoustic cavitation refers to the rapid formation and collapse of small bubbles in a liquid, resulting in localized high temperatures and pressures. This phenomenon accelerates the transesterification process, leading to higher biodiesel conversion rates. Studies have highlighted the role of ultrasound-induced cavitation in promoting biodiesel synthesis.[20] However, it should be noted that at ultrasonic amplitudes exceeding the optimal range (>85%), there is a risk of initiating the saponification process, which can impede biodiesel synthesis.[18]

Optimization Process. The results obtained from our study indicate that the experimental process can be further optimized by conducting additional tests using the optimizer tool in MINITAB. Based on our findings, the highest biodiesel yield achieved was 97.3%, with a desirability score of 0.928. This optimal yield was obtained under specific conditions: a catalyst amount of 1.15 g, a MeOH/PF ratio of 5.45:1, and an ultrasonic amplitude of 83.8%, as shown in Figure 5. To validate the numerical optimization results, we performed supplementary experiments in triplicate, closely following the optimal parameters. These parameters included a catalyst ($CoFe_2O_4$) amount of 1.2 g, a MeOH/PF ratio of 5.5:1, and an ultrasonic amplitude of 85%. The observed biodiesel yield removal efficiency in the experimental setup was 96.5 ± 0.06%, which closely aligns with the predicted value. This demonstrates the agreement between experimental outcomes and predictive models, further supporting the validity and reliability of our findings.

Biodiesel Profile. The principal composition of the analyzed biodiesel comprises a variety of fatty acid methyl esters (FAMEs) with distinctive carbon chain lengths and saturation levels, as outlined in Table S1. Among the identified FAMEs, the predominant constituents are methyl esters of 9-

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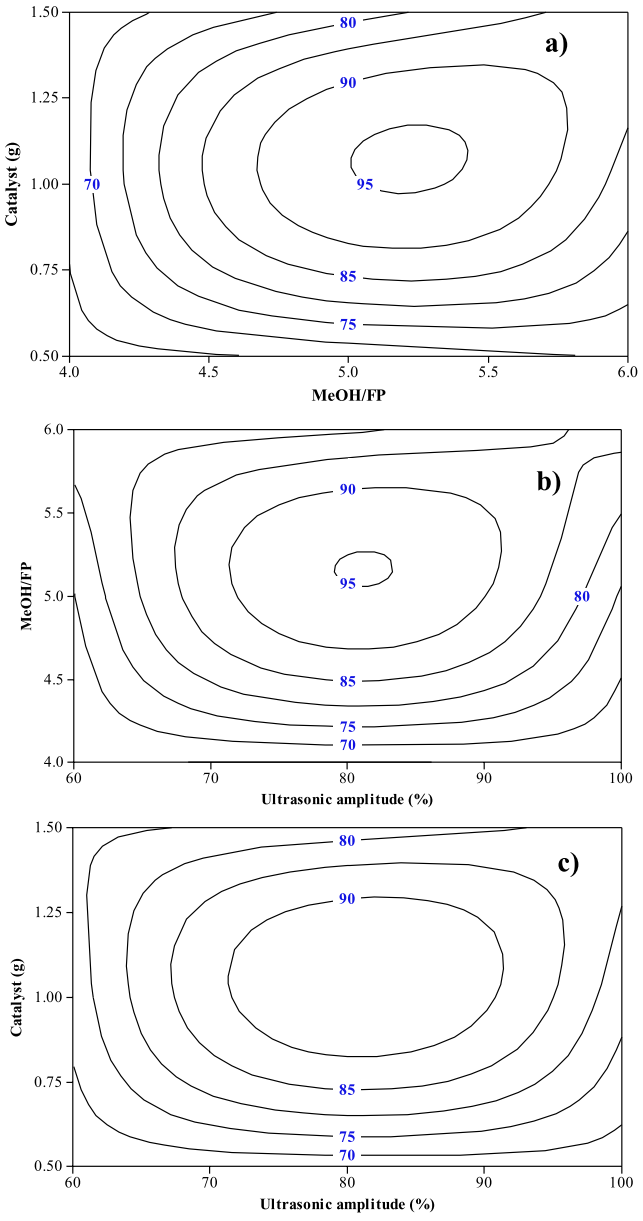

Figure 4. Contour plot of (a) catalyst vs MeOH/PF, (b) MeOH/PF vs ultrasonic amplitude, and (c) catalyst vs ultrasonic amplitude.

octadecenoic acid (oleic acid), constituting 26.23% of the composition, and hexadecanoic acid (palmitic acid), accounting for 25.46% of the total. The fatty acid profile of this biodiesel encompasses a diverse range of saturated (lacking double bonds) and unsaturated (containing one or more double bonds) fatty acids, significantly influencing the overall biodiesel properties. This observation aligns with prior research.[3] Significantly, the calculated kinematic viscosity of biodiesel at 40 °C is 4.842 mm^2/s (Table S2), a vital characteristic with potential implications for engine performance. Importantly, this value falls within the acceptable range of 1.9 to 6.0 mm^2/s at 40 °C, complying with the ASTM D6751 and EN 14214 biodiesel standards.[13]

The specific gravity of biodiesel, determined at 894 kg/m^3, emerges as a significant parameter influencing various aspects, including energy content per unit volume, fuel system design, and engine power output. Importantly, this value falls within the typical biodiesel range of 860 to 900 kg/m^3, consistent with the findings of an earlier study.[21] The acid value of biodiesel is measured at 0.21 mg of KOH/g, indicating the presence of free fatty acids. The observed low acid value signifies a high-quality biodiesel product, as higher values could lead to engine component corrosion and reduced shelf life.[7] The biodiesel's iodine value is recorded at 68.2 g of I_2/100 g, providing insights into its degree of unsaturation. This parameter is noteworthy, as higher iodine values indicate greater unsaturation, potentially raising the risk of oxidation and polymerization, which could impact engine performance through deposit formation. In this case, the moderate iodine value reflects a well-balanced blend of saturated and unsaturated fatty acids. Furthermore, the minimal content of total glycerol (0.021% mol/mol) and methanol (0.005% mol/mol) highlights the high efficiency of the transesterification process. Efficient removal of glycerol and methanol during biodiesel production is essential to mitigate their negative effects on fuel quality and performance.[6]

Comparing PF-derived biodiesel with other biodiesels reveals distinct patterns. Soybean oil-derived biodiesel typically exhibits higher levels of linoleic acid (C18:2) and lower levels of stearic acid (C18:0), resulting in a higher iodine value and increased vulnerability to oxidation. On the contrary, palm oil biodiesel often showcases elevated concentrations of palmitic acid (C16:0) and decreased oleic acid (C18:1), yielding a more saturated profile, reduced iodine value, and improved resistance to oxidation. However, this comes with the potential for an increase in viscosity.[19,20,22] In this context, PF-derived biodiesel emerges as a well-balanced composition, featuring a diverse range of FAMEs and demonstrating favorable physical and chemical properties. Nonetheless, further investigations are necessary to comprehensively assess its suitability for

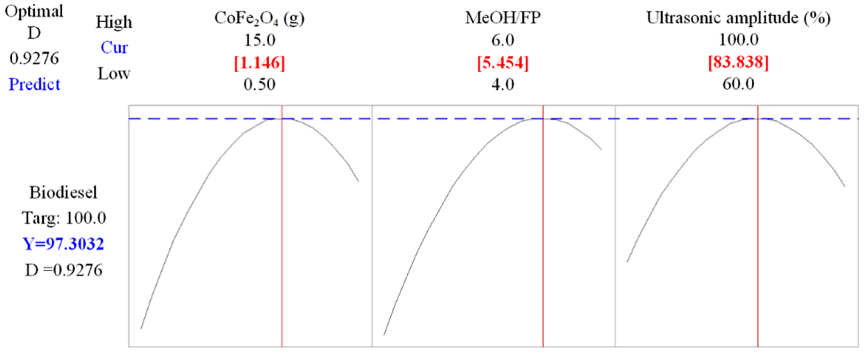

Figure 5. Response optimization plot for maximum biodiesel synthesis.

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biodiesel applications, including evaluations of oxidative stability, cold filter plugging point (CFPP), and cetane number.[23] These assessments provide insights into biodiesel's resistance to oxidation, ability to perform in low temperatures and combustion quality.

LCA Results. The characterization phase in LCA involves allocating the environmental impacts of each stage to specific impact categories using midpoint and end point indicators.

Assessment of the Midpoint Indicator. Based on midpoint estimates, the LCA findings indicate that the production of 1 kg of biodiesel results in a global warming potential equivalent to 0.21 kg of CO_2. Figure 6 or Table S3 clearly illustrates the different environmental impacts of the two main processes involved in ultrasonic biodiesel production.

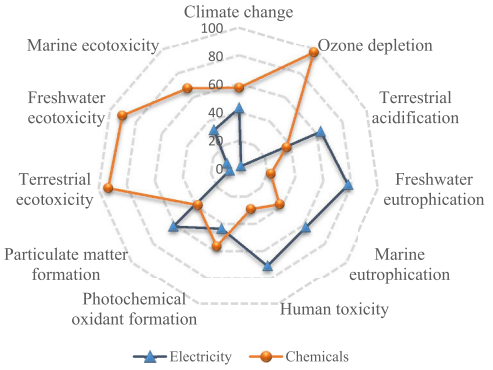

Figure 6. Midpoint analysis of the impact categories from chemicals and electricity.

The capacitive process involved in biodiesel synthesis notably impacts acidification and eutrophication. This is evident in the metrics for terrestrial acidification, freshwater eutrophication, and marine eutrophication, which contribute 63.34, 77.53, and 62.3%, respectively. These contributions can be attributed to the energy-intensive nature of biodiesel production, resulting in emissions such as sulfur dioxide (equivalent to 0.0005 kg of SO_2), nitrogen oxides (equivalent to 0.0001 kg of SO_2), and significant amounts of phosphate (equivalent to 0.0004 kg of P) and nitrate (equivalent to 0.0000008 kg of N).

In our analysis, ecological toxicity was also identified as a significant concern, primarily due to the use of methanol (MeOH) and the creation of catalytic compounds. The indicators for terrestrial ecotoxicity, freshwater ecotoxicity, and marine ecotoxicity exhibit substantial values, contributing 93.19, 90.48, and 67.39%, respectively. These results emphasize the significant ecological impact of these processes in biodiesel production.

End Point Indicator Assessment. By utilizing the ReCiPe v1.13 End point (H) framework, our analysis encompassed a comprehensive evaluation of the environmental impact, considering implications on human health, ecological systems, and resource utilization. Regarding human health, the assessment focused on the indirect environmental contamination resulting from industrial power generation and production processes. Such pollution can worsen related illnesses, prolong their duration, increase their prevalence, and harm the human lifespan. From an ecological perspective, the evaluation considered factors such as acidification, ecotoxicity, and eutrophication. The ecological balance is disrupted by elements such as nitrogen, cobalt, and iron, which adversely affect the overall health and vitality of ecosystems. Regarding resource assessment, the focus is on evaluating the rates of resource depletion and energy consumption throughout the process. The cumulative impact on human health, ecological systems and resources for the entire process is estimated to be 7.68, 4.12 and 19.07 mPt, per reference unit, respectively, as depicted in Figure 7. The above values reflect the combined effects of biodiesel production on human health, ecological systems, and resource utilization. Table 4 concisely summarizes various LCA scenarios and applications involving the Recepi tool for generating biodiesel from renewable sources. The results indicate that the RF biodiesel production process demonstrates limited environmental impact, underscoring its potential for industrial feasibility.

CONCLUSIONS

This study optimized biodiesel production from *Pangasius* fat (PF) using a Box-Behnken experimental design. Critical parameters substantially influenced biodiesel yield including magnetic $CoFe_2O_4$ catalyst dosage, methanol-to-fat ratio, and ultrasonic amplitude. An impressive yield of 97.3% was attained by precisely manipulating these factors. The regression model constructed following experimental results validated its predictive accuracy for biodiesel synthesis. The resulting biodiesel derived from PF met the required viscosity, specific gravity, acid value, and iodine value, confirming its suitability for diverse biodiesel applications. These findings emphasize the potential of PF as a valuable feedstock for biodiesel production. Environmental impact indices, namely, human health, ecosystems, and resources, were calculated at

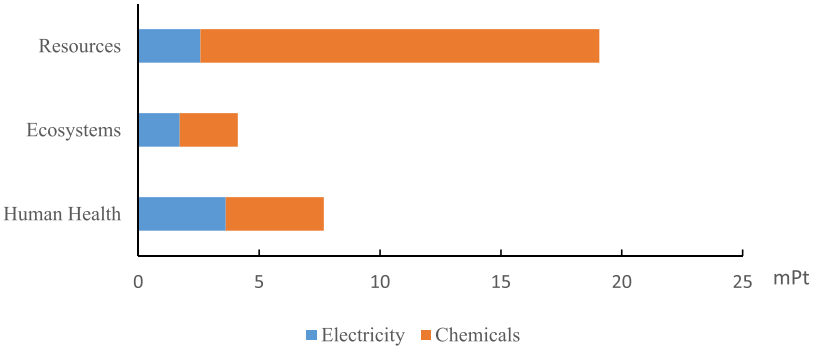

Figure 7. Attributional LCA results for 1 kg of biodiesel produced from *Pangasius* fat.

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Table 4. Summary of the Investigation with the Recipe Tool for the Production of Biodiesel

target	boundary	function unit	impact	ref.
microalgae	cradle to gate	1 kg biodiesel	880 mPt	24
date seed	cradle to gate	1000 kg biodiesel	216.97 Pt (reused solvent and catalysts)	4
			357.41 Pt (not reusable)	
vine shoot waste	cradle to gate	1 kg bioethanol	9.3 Pt	25
solaris seed tobacco	cradle to gate	1 kg biodiesel	HH: 1.07×10^{-5} Daly	26
			ES: 7.13×10^{-8} species year^{-1}	
			R: $1.42	
PF	gate to gate	1 kg biodiesel	30.87 mPt	this study

7.68, 4.12, and 19.07 mPt, respectively. Considering actual biodiesel production yield, it is essential to account for practical factors such as pisciculture, lipid extraction, and subsequent fat refinement. These elements may further enhance yield when employing this method.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.3c04461.

Main ingredients; characteristic of the biodiesel from *Pangasius* fat; and midpoint impact categories of the biodiesel production (PDF)

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Notes

The authors declare no competing financial interest.

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