181 *Egypt. J. Chem.* **Vol. 68**, No. 4. pp. 395 - 404 (2025)

Egyptian Journal of Chemistry

http://ejchem.journals.ekb.eg/

Optimization for Synthesis of Solid Alcohol from Supernatant-Waste Cooking Oil using Box-Behnken Design

Heri Septya Kusuma[1,*], Muhammad Redo Ramadhan[1], Dyan Hatining Ayu Sudarni[2], Debora Engelien Christa Jaya[1], Dwi Kurnia Afifah[1], Safinah Annajah Nasution[1], Deva Meida Fachri[1], Ratu Kalya Mongilong[1]

[1]*Departement of Chemical Engineering, Faculty of Industrial Engineering, Universitas Pembangunan Nasional "Veteran" Yogyakarta, Indonesia*

[2]*Departement of Chemical Engineering, Faculty of Engineering, Universitas PGRI Madiun, Indonesia*

Abstract

This study investigates the optimization of solid alcohol synthesis from Supernatant-Waste Cooking Oil (S-WCO) using Response Surface Methodology (RSM) combined with Box-Behnken Design (BBD). The primary objective was to determine the optimal conditions for maximizing the yield of solid alcohol by systematically varying three key parameters: mass of oil (5, 10, 15 g), NaOH to oil ratio (0.100, 0.175, 0.250 g/g), and heating time (20, 30, 40 minutes). The experimental findings revealed that the yield of solid alcohol ranged from 81.20% to 87.67%, with the highest yield achieved at mass of oil of 11.14 g, NaOH to oil ratio of 0.20 g/g, and heating time of 25.70 minutes. The desirability value for these conditions was calculated to be 0.911, indicating the process's high efficiency. Analysis of variance (ANOVA) substantiated the model's significance, highlighting the critical influence of both linear and quadratic terms, particularly the NaOH to oil ratio and heating time.The results have profound implications for scaling up the process in industrial contexts, offering a promising solution for waste management and alternative energy production. Future research should explore the potential of alternative catalysts and further process optimizations to enhance the economic and environmental benefits of this method.

Keywords: Box-Behnken Design (BBD); Optimization; Response Surface Methodology (RSM); Solid Alcohol Synthesis; Waste Cooking Oil (WCO)

1. Introduction

The global energy crisis is increasingly exacerbated by the rapid depletion of fossil fuels, which not only jeopardizes energy security but also significantly contributes to greenhouse gas emissions, thereby accelerating climate change [1]. In response, the scientific community has intensified efforts to explore alternative and sustainable energy sources that can mitigate these environmental impacts. Among the most promising alternatives are biofuels such as ethanol and methanol, which offer superior physicochemical properties and are derived from abundant raw materials through well-established production technologies [2]. Unlike their liquid counterparts, solid alcohols present additional advantages, including extended burning times, more consistent flame temperatures, improved efficiency, and ease of use, making them particularly valuable in sectors like catering, tourism, and restaurants [3].

While biofuels like ethanol and methanol hold significant potential, the disposal of waste cooking oil (WCO) presents both a growing challenge and a unique opportunity. WCO, a byproduct of the food industry, undergoes substantial chemical degradation after repeated use, leading to increased viscosity, acidity, and the formation of harmful compounds [4,5]. Improper disposal of WCO poses severe environmental and public health risks [6]. Thus, there is an urgent need to develop sustainable methods for converting WCO into valuable resources. Although transforming WCO into biodiesel is an effective strategy, this process often requires extensive pretreatment, which increases production costs and may compromise product quality [7]. This research proposes the conversion of WCO into solid alcohol as a more practical and efficient alternative, addressing both the environmental challenges associated with WCO and the global demand for sustainable fuels.

Recent advancements in the recycling of waste cooking oil (WCO) into solid alcohol offer a promising alternative to traditional biodiesel production. The process of synthesizing solid alcohol involves using WCO as an alcohol absorbent, where it undergoes saponification to form fatty acid sodium salts and glycerol through a reaction with strong bases like

*Corresponding author e-mail: heriseptyakusuma@gmail.com (Heri Septya Kusuma).
Receive Date: 07 July 2024, Revise Date: 30 August 2024, Accept Date: 02 September 2024
DOI: 10.21608/ejchem.2024.300483.9922

sodium hydroxide [8]. This saponification process enables the creation of a solid absorbent system that can be efficiently converted into solid alcohol. Prior research has demonstrated that optimizing this process can be achieved by manipulating critical variables such as the NaOH to oil ratio, the mass of oil, and the heating time, as highlighted in the work of Xiong et al. (2019) [7]. These studies suggest that this approach to WCO recycling, which circumvents the complex pretreatment required for biodiesel production, can lead to the efficient production of a sustainable solid fuel [7].

However, despite the progress in converting WCO into solid alcohol, most existing research has been confined to laboratory-scale experiments and has not fully explored the optimization of the synthesis process using systematic experimental designs. A review of the literature indicates a gap in the application of advanced optimization techniques, such as Response Surface Methodology (RSM) in combination with Box-Behnken Design (BBD), to refine the synthesis conditions for maximizing solid alcohol yield. While previous studies, such as those by Baghani et al. (2022) [3] and Xiong et al. (2019) [7], demonstrate the potential of these techniques, they fall short of providing comprehensive optimization across all relevant parameters. This gap underscores the opportunity to apply RSM-BBD to systematically investigate the effects of NaOH to oil ratio, mass of oil, and heating time on the yield of solid alcohol, thereby advancing the knowledge base in sustainable fuel production

The objective of this study is to optimize the synthesis of solid alcohol from Supernatant-Waste Cooking Oil (S-WCO) utilizing Response Surface Methodology (RSM) in conjunction with Box-Behnken Design (BBD). The novelty of this research lies in the systematic application of RSM-BBD to identify the optimal conditions that maximize solid alcohol yield, with a particular emphasis on the NaOH to oil ratio, mass of oil, and heating time. This approach not only addresses the pressing environmental issue of WCO disposal but also contributes to the development of a sustainable and efficient method for producing solid alcohol as an alternative fuel. Although the scope of this study is confined to laboratory-scale experiments using pro-analytical alcohol, the results are anticipated to have significant implications for industrial-scale production. Future research should explore the use of technical alcohol and alternative catalysts to further enhance the sustainability and cost-effectiveness of the process.

2. Materials and methods

2.1. Materials

The materials used in this study were sourced and prepared as follows:

a. Supernatant-Waste Cooking Oil (S-WCO): Waste Cooking Oil (WCO) was collected from a local fried banana vendor, “Pigope,” situated in the Seturan area, Depok District, Sleman Regency, Yogyakarta Special Region. The WCO was initially filtered using an Eagle Tea Strainer SS-12 to remove large particulate impurities. The filtered oil was then centrifuged at 3,000 rpm for 20 minutes, resulting in the separation of two distinct layers: Supernatant-Waste Cooking Oil (S-WCO) and Bottom-Waste Cooking Oil (B-WCO). Only the S-WCO was utilized in the subsequent synthesis process.
b. Ethanol (p.a.): Pro-analytical grade ethanol was employed as the solvent in the synthesis of solid alcohol. The high purity of this ethanol was crucial for ensuring the reliability and reproducibility of the experimental results.
c. Sodium Hydroxide (NaOH): Sodium hydroxide was used as the catalyst in the synthesis process. A solution of NaOH was prepared by dissolving it in distilled water, creating various NaOH to oil ratios (0.100, 0.175, and 0.250 g/g) as required by the experimental design.
d. Distilled Water: Distilled water was used in the preparation of the NaOH solution and for other necessary procedures throughout the synthesis process.

2.2. Methods

2.2.1. ***Preparation of Solid Alcohol***

The synthesis of solid alcohol was carried out using a modified method based on previous research by Xiong et al. (2019) [7]. The procedure consisted of the following steps:

a. Dissolution: Varying masses of S-WCO (5 g, 10 g, and 15 g) were dissolved in ethanol (50 g, 100 g, and 150 g) within a 250 mL beaker, resulting in a yellow-colored solution.
b. NaOH Solution Preparation: Sodium hydroxide was dissolved in 3 mL of distilled water to create a solution with different NaOH to oil ratios (0.100, 0.175, and 0.250 g/g).
c. Heating: The mixture of S-WCO and ethanol was heated for 10 minutes. Following this, the NaOH solution was added, and the mixture was subjected to continuous heating and stirring for varying durations (20 minutes, 30 minutes, and 40 minutes), as dictated by the experimental design.
d. Cooling and Solidification: After the prescribed heating period, the solution was quickly poured into molds and allowed to cool to room temperature over 2 hours. The resulting solid alcohol, characterized by its light-yellow and opaque appearance, was then weighed to determine the yield.

2.2.2. ***Experimental Design and Optimization***

The optimization of solid alcohol synthesis was performed using Response Surface Methodology (RSM) in conjunction with a Box-Behnken Design (BBD). The independent variables investigated in this study were:

a. Mass of Oil (g): 5 g, 10 g, 15 g
b. NaOH to Oil Ratio (g/g): 0.100, 0.175, 0.250
c. Heating Time (min): 20 minutes, 30 minutes, 40 minutes

The primary response variable measured was the yield of solid alcohol, expressed as a percentage. The experimental design comprised 17 runs as prescribed by the BBD matrix. The collected data was utilized to develop a quadratic regression model, which elucidates the relationship between the independent variables and the yield of solid alcohol.

2.2.3. ***Statistical Analysis***

The experimental data was analyzed using analysis of variance (ANOVA) to evaluate the significance of the model and the contributions of individual terms. Model adequacy was further assessed through diagnostic plots, including normal probability plots and plots of residuals versus predicted values. Optimization was conducted to identify the conditions that maximized the yield of solid alcohol. The desirability function was employed to pinpoint the optimal solution, balancing the independent variables to achieve the highest possible yield.

The experimental outcomes were interpreted in the context of existing literature, and the findings were discussed with respect to their scientific significance and practical applications.

3. Results and Discussion

3.1. Effect of Mass of Oil, NaOH to Oil Ratio, and Heating Time on Solid Alcohol Yield

The optimization of solid alcohol synthesis from Supernatant-Waste Cooking Oil (S-WCO) was conducted by analyzing the effects of three critical variables: mass of oil, NaOH to oil ratio, and heating time. The experimental design, comprising 17 runs, allowed for the yield of solid alcohol to be measured as a percentage (Table 1). The results demonstrate that each of these variables—mass of oil, NaOH to oil ratio, and heating time—significantly impacted the yield of solid alcohol. The data reveal that a mass of oil of 10 g generally resulted in the most considerable variation in yields, with values ranging from 81.8924% to 87.6717%. Notably, the highest yield of 87.6717% was achieved using 10 g of oil, a NaOH to oil ratio of 0.175, and a heating time of 30 minutes. In contrast, the lowest yield of 81.1964% was observed with 5 g of oil, a NaOH to oil ratio of 0.175, and a heating time of 40 minutes. These findings underscore the importance of optimizing the interaction between these variables to maximize solid alcohol production. The NaOH to oil ratio emerged as another critical factor, with yields varying significantly across different ratios. For instance, at a ratio of 0.100, yields ranged from 81.8924% to 86.4137%, whereas a ratio of 0.250 resulted in yields between 83.3615% and 86.8239%. Additionally, heating time had a pronounced impact on yield; shorter heating times (20 minutes) generally resulted in higher yields, while extended heating times (40 minutes) tended to reduce the yield. These findings are consistent with previous research on optimizing solid alcohol synthesis, particularly in highlighting the significance of key variables such as the NaOH to oil ratio and heating time. For example, Xiong et al. (2019) [7] demonstrated that achieving an optimal balance of these variables is crucial for maximizing solid alcohol yield. However, the present study advances this understanding by systematically applying Response Surface Methodology (RSM) combined with Box-Behnken Design (BBD), providing a more precise and refined optimization process.When compared to the work of Baghani et al. (2022) [3], it is clear that the choice of NaOH to oil ratio and mass of oil plays a pivotal role in determining the efficiency of solid alcohol synthesis. While Baghani et al. (2022) [3] emphasized the use of sodium stearate and other bases as alcohol sorbents, this study underscores the importance of the specific NaOH to oil ratio and heating duration in significantly influencing the final yield.

Moreover, the results of this study corroborate the findings of Dong et al. (2021) [9], who observed that prolonged heating times could decrease yield due to the potential degradation of alcohol at elevated temperatures. The decrease in yield with extended heating time observed in this study further underscores the necessity of carefully controlling heating duration to optimize the production process.

The findings of this study hold both scientific and practical significance. Scientifically, the research advances the understanding of solid alcohol synthesis from waste cooking oil (WCO) by incorporating Response Surface Methodology coupled with Box-Behnken Design (RSM-BBD) into the optimization process. This methodological integration provides a deeper insight into the interactions among different variables, thereby improving the predictability and efficiency of solid alcohol production. As a result, the study makes a valuable contribution to the field of sustainable biofuel research.

From a practical standpoint, the results have significant implications for industries focused on waste management and biofuel production. The optimized process for converting Supernatant-WCO (S-WCO) into solid alcohol offers a cost-effective and environmentally sustainable solution for managing WCO, a waste product that poses considerable disposal challenges. By identifying the optimal conditions that maximize yield, this research supports the scalability of solid alcohol production to an industrial level, where it could serve as a viable alternative to traditional fuels across various sectors.

Furthermore, the ability to produce solid alcohol using relatively simple and accessible materials and methods has the potential to facilitate broader adoption of this technology, particularly in regions where WCO is abundant but effective disposal methods are lacking. This contributes to energy security and environmental sustainability by reducing waste and providing a renewable energy source. In summary, this study not only enhances the scientific understanding of solid alcohol synthesis but also underscores its practical viability as a sustainable energy solution, with the potential to generate substantial environmental and economic benefits.

3.2. Analysis of Variance (ANOVA)

The analysis of variance (ANOVA) was employed to assess the significance of the factors influencing the synthesis of solid alcohol from Supernatant-Waste Cooking Oil (S-WCO). As shown in Table 2, the model was found to be statistically significant, with a F-value of 5.71 and a p-value of 0.0158, indicating that the model terms have a significant impact on the response variable, which is the yield of solid alcohol. Notably, significant model terms include the linear term for heating time (C) and the quadratic terms for both the mass of oil (A^2) and heating time (C^2), each with p-values less than 0.05. These findings suggest that both the linear and quadratic effects of these factors are critical in optimizing the synthesis process.

The adequacy of the fitted model was further confirmed by a "Lack of Fit" test, which revealed that the "Lack of Fit F-value" was not significant (p = 0.4038), indicating that the model fits the experimental data well. This conclusion is further supported by the plot in Fig. 1, which compares predicted yields with actual yields. Although some deviations are present, the predicted values closely align with the actual data points, underscoring the model's reliability in predicting outcomes within the experimental design space.

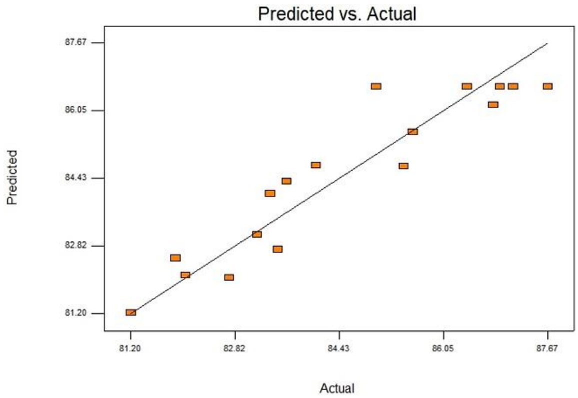

Fig. 1. Relationship between predicted and actual yields in the synthesis of solid alcohol from Supernatant-Waste Cooking Oil (S-WCO)

The results of this study are consistent with previous research on the synthesis of solid alcohol from WCO, particularly regarding the critical influence of the NaOH to oil ratio and heating time on yield. Similar conclusions were drawn by Xiong et al. (2019) [7], who also identified these variables as key factors in optimizing solid alcohol production. However, the present study advances this understanding by employing a more rigorous statistical approach, utilizing Response Surface Methodology (RSM) combined with Box-Behnken Design (BBD), which allows for a more precise evaluation of interaction effects and quadratic terms.

Compared to the work of Baghani et al. (2022) [3], which emphasized the importance of sodium stearate as an alcohol sorbent, this study focused on the role of NaOH and its interactions with other variables. The significance of the quadratic terms identified in this study, particularly for heating time, suggests that the reaction kinetics involved in solid alcohol synthesis are complex, and optimizing these conditions can result in substantial yield improvements.

Additionally, the findings align with those of Dong et al. (2021) [9], who discussed the potential adverse effects of prolonged heating. This study corroborates their observations, as higher heating times were associated with reduced yields, indicating that there is an optimal heating time range. Exceeding this range likely leads to the degradation of reactants or the loss of alcohol, thereby diminishing the efficiency of the synthesis process.

The findings of this study are significant both in advancing the scientific understanding of solid alcohol synthesis and in offering practical solutions for waste cooking oil (WCO) recycling. Scientifically, the identification of significant linear and quadratic effects for key variables, such as heating time and the NaOH to oil ratio, provides deeper insights into the complex interactions that influence the synthesis process. The application of ANOVA and response surface methodology enhances the precision of these insights, resulting in a robust model capable of predicting yields under varying conditions.

From a practical perspective, these findings have crucial implications for the scalability of solid alcohol production. The ability to optimize process conditions to achieve high yields suggests that industries focused on waste management and renewable energy production can effectively adopt this method to convert WCO into a valuable, sustainable fuel source. The simplicity of the chemical process and the accessibility of the required materials further increase the feasibility of this approach, especially in regions with abundant WCO but limited access to advanced waste processing technologies.

Additionally, the strong correlation between predicted and actual yields indicates that the model developed in this study could be effectively applied in industrial settings to improve process efficiency, reduce waste, and enhance the economic viability of solid alcohol as an alternative fuel. This advancement could have far-reaching environmental benefits by mitigating the environmental impact of WCO disposal and contributing to global efforts to transition towards more sustainable energy sources.

3.3. 2D and 3D Response Surface Plots

Response Surface Methodology (RSM) combined with Box-Behnken Design (BBD) was employed to optimize the synthesis of solid alcohol from Supernatant-Waste Cooking Oil (S-WCO). The experimental outcomes, illustrated in 2D (Fig. 2) and 3D (Fig. 3) response surface plots, elucidate the effects of the mass of oil, NaOH to oil ratio, and heating time on the yield of solid alcohol.

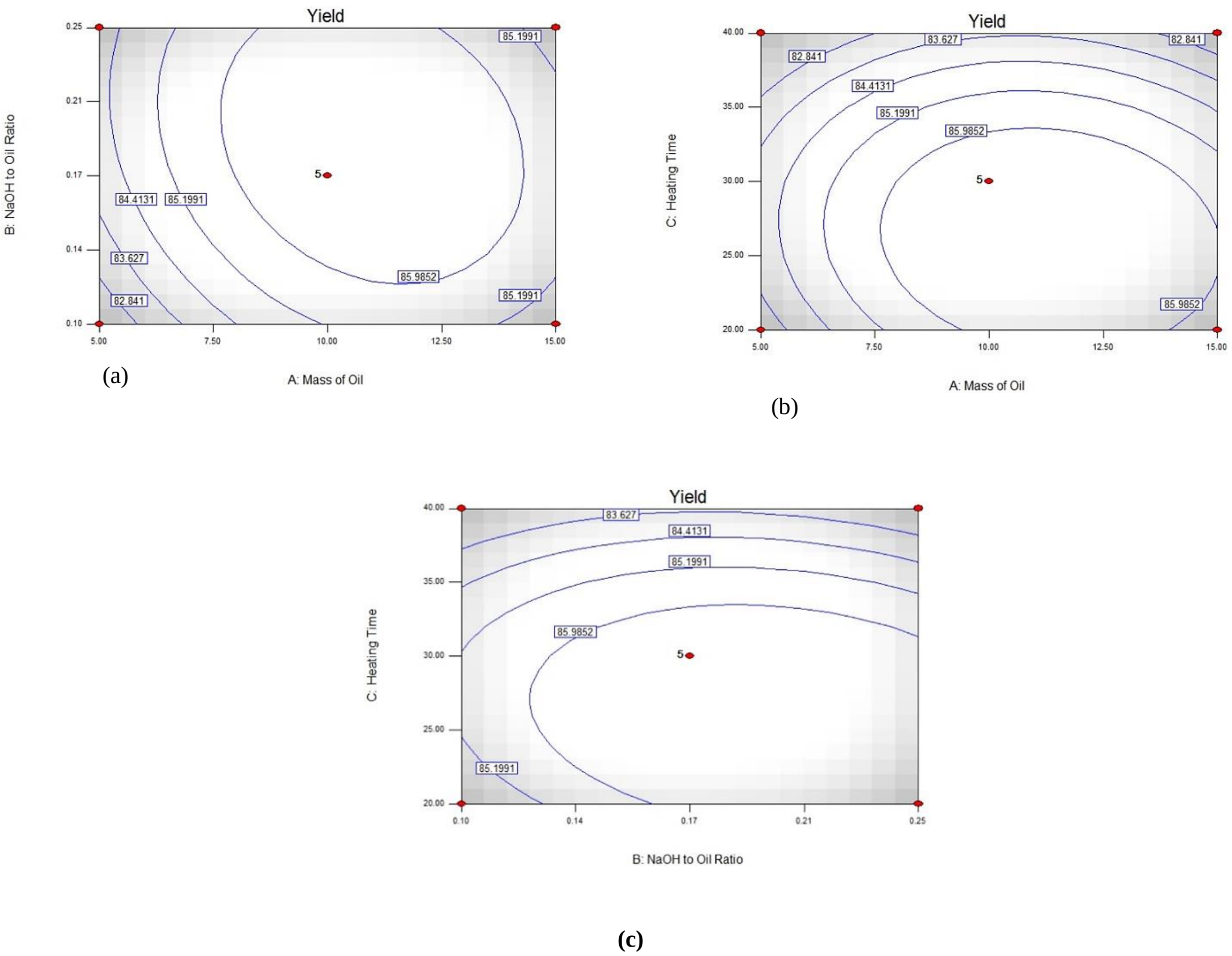

Fig. 2. 2D response surface plots showing solid alcohol yield as a function of interactions between: (a) A and B; (b) A and C; and (c) B and C; where A: Mass of Oil; B: NaOH to Oil Ratio; C: Heating Time

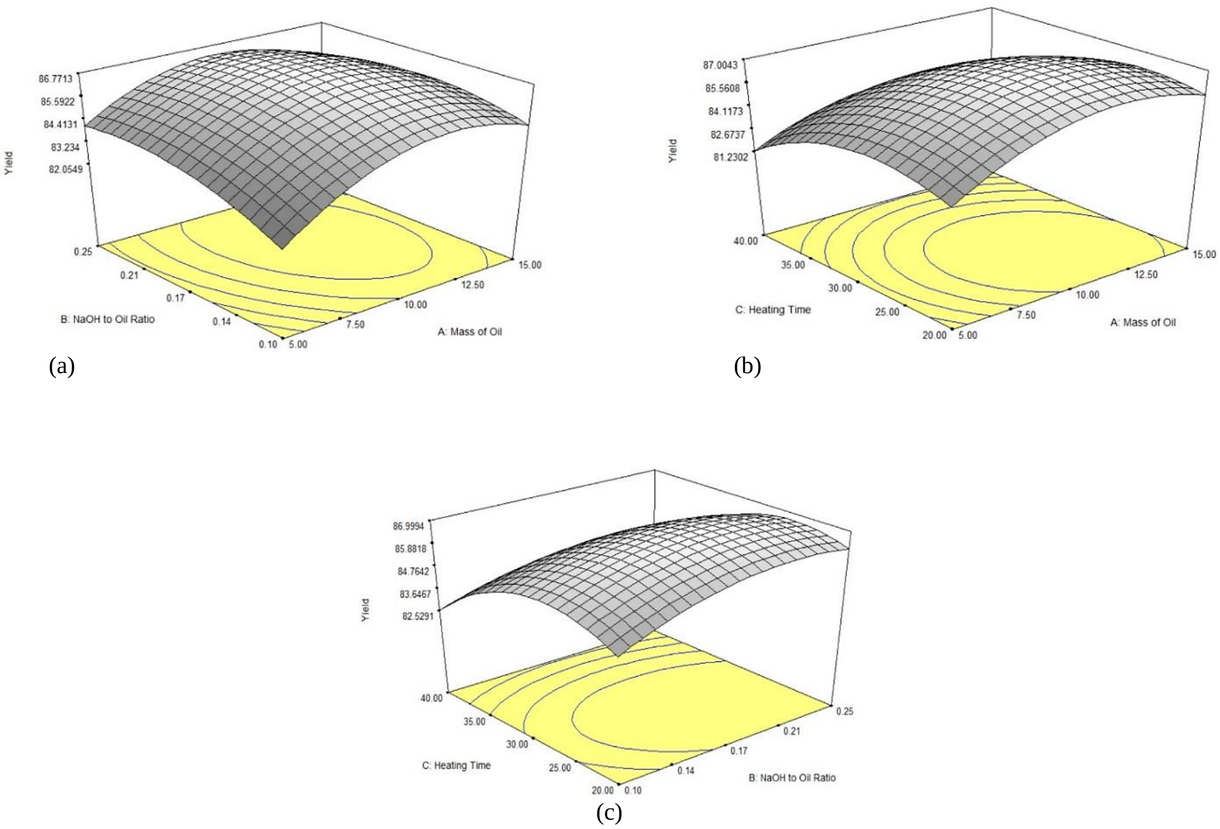

Fig. 3. 3D response surface plots showing solid alcohol yield as a function of interactions between: (a) A and B; (b) A and C; and (c) B and C; where A: Mass of Oil; B: NaOH to Oil Ratio; C: Heating Time

The plots reveal that the mass of oil and NaOH to oil ratio have a significant impact on the yield. Specifically, when the NaOH to oil ratio ranges between 0.17 g/g and 0.25 g/g and the mass of oil is between 7.50 g and 12.50 g, the yield of solid alcohol exceeds 85.9852%, indicating an optimal range for these parameters. However, increasing the NaOH to oil ratio beyond 0.25 g/g and the mass of oil beyond 12.50 g results in a decline in yield, as indicated by the outer contours of the response surface.

Similarly, the interaction between the mass of oil and heating time exhibits a comparable trend, where the yield increases with both parameters up to a certain point. Beyond this threshold, particularly when heating time exceeds 30 minutes, the response surface inverts, signaling a reduction in yield.

These findings align with previous research on solid alcohol synthesis, particularly regarding the optimal ranges for NaOH to oil ratio and mass of oil, which are consistent with those reported by Xue et al. (2019) [10]. This study, however, offers a more nuanced understanding by providing explicit visual and quantitative analyses through 2D and 3D response surface plots, thereby enhancing the comprehension of how these variables interact to influence yield—a level of detail that was less emphasized in earlier studies.

Additionally, the observed decrease in yield at higher NaOH to oil ratios and extended heating times aligns with the findings of Tan et al. (2019) [11], who reported that suboptimal heating conditions, especially near the boiling point of methanol, can result in reduced yields due to the evaporation of reactants. This study builds on those findings by demonstrating that not only temperature but also the precise interaction between NaOH to oil ratio and heating time plays a critical role in determining the outcome.

The results derived from the response surface plots are particularly significant as they offer a comprehensive guide for optimizing the synthesis of solid alcohol from S-WCO. Scientifically, this study deepens the understanding of the key variables that affect solid alcohol yield and their interactions. The precise identification of optimal ranges for NaOH to oil ratio, mass of oil, and heating time facilitates more efficient and predictable outcomes in the synthesis process.

From a practical perspective, these findings hold considerable relevance for industries aiming to adopt sustainable practices by converting waste cooking oil into valuable solid fuels. The ability to optimize production parameters based on the detailed insights provided by this study enables industries to maximize yields while minimizing waste and costs. This has substantial implications for the scalability of solid alcohol production, enhancing its viability and attractiveness for large-scale implementation.

Moreover, the visualization of data through response surface plots offers a powerful tool for decision-makers within these industries, allowing them to easily interpret complex interactions and make informed adjustments to their processes. This approach not only contributes to the field of sustainable biofuel research but also provides actionable insights that can facilitate the practical application of these technologies.

3.4. Model Adequacy Checking

The adequacy of the model used to synthesize solid alcohol from Supernatant-Waste Cooking Oil (S-WCO) was assessed through various diagnostic plots, including the normal probability plot of residuals and the plot of residuals versus predicted values. Fig. 4, the normal probability plot, demonstrates that the residuals generally align along a straight line, indicating that the assumption of normality is reasonably satisfied. This suggests that the errors are normally distributed, which is crucial for the validity of the statistical inferences drawn from the model.

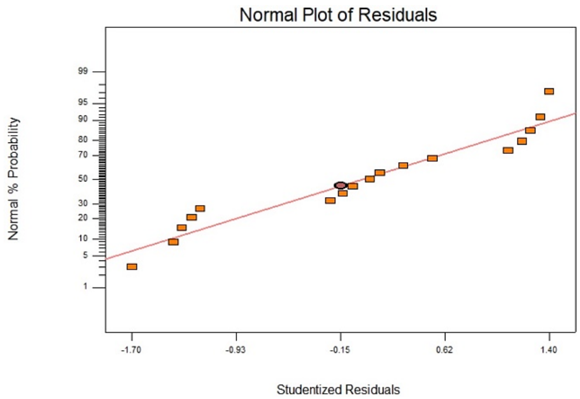

Fig. 4. Diagnostic plot for the synthesis model of solid alcohol from Supernatant-Waste Cooking Oil (S-WCO): Normal % Probability vs. Studentized Residuals

Fig. 5, which illustrates the residuals versus predicted values, shows that the residuals are randomly scattered around zero and fall within the range of -3 to +3. This random distribution indicates that the model does not exhibit any discernible patterns or systematic biases, further supporting the conclusion that the model is adequate for predicting the yield of solid alcohol within the range of studied variables.

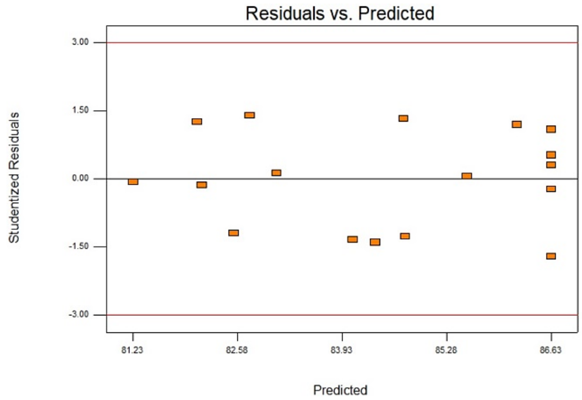

Fig. 5. Diagnostic plot for the synthesis model of solid alcohol from Supernatant-Waste Cooking Oil (S-WCO): Studentized Residuals vs. Predicted Values

The results of the model adequacy checking are consistent with established practices in statistical modeling. As emphasized by Gunst et al. (1996) [12], validating model assumptions—particularly the normality of residuals and the absence of patterns in residual plots—is essential for ensuring accurate predictions and reliable data interpretations. In this study, both the normal probability plot and the residuals versus predicted values plot confirm that the model meets these critical criteria. These findings align with those of previous studies, such as Li et al. (2004) [13], who used similar diagnostic methods to validate models in chemical engineering processes.

However, it is important to note that while the residuals generally conform to the expected distribution, there are a few points that deviate from the straight line in the normal probability plot. These deviations indicate the presence of some noise or unexplained variability in the data, which might be addressed by refining the model or investigating additional variables. This observation aligns with the findings of Hapid et al. (2024) [14], who suggested that even well-fitting models may benefit from further optimization to account for minor deviations in residuals.

The findings from the model adequacy checking are critical for both the scientific rigor of this study and its practical applications. Scientifically, confirming that the residuals are normally distributed and that there is no systematic bias in the model ensures the validity of the conclusions drawn from the response surface methodology (RSM). This validation adds credibility to the optimization results, suggesting that the identified optimal conditions for solid alcohol synthesis are reliable and can be confidently applied in practice.

From a practical standpoint, the adequacy of the model implies that industries implementing the optimized synthesis process can do so with a reasonable expectation of consistent and predictable outcomes. The random distribution of residuals around zero indicates that the model can accurately predict yields within the studied range of conditions, reducing the risk of unexpected results during scale-up or industrial application. This is particularly significant in the context of waste management and biofuel production, where efficiency and reliability are crucial to both economic viability and environmental sustainability. In summary, the satisfactory results of the model adequacy checking confirm that the empirical model developed in this study is robust and well-suited to guide the practical synthesis of solid alcohol from S-WCO, offering a valuable tool for industries seeking to adopt more sustainable practices.

3.5. Determination of Optimum Condition

The optimization of solid alcohol synthesis from Supernatant-Waste Cooking Oil (S-WCO) was performed using Response Surface Methodology (RSM) in conjunction with Box-Behnken Design (BBD). The goal of the optimization was to identify the conditions that would maximize yield by adjusting three critical variables: mass of oil, NaOH to oil ratio, and heating time. The experimental results indicated that the yield of solid alcohol ranged from 81.1964% to 87.6717%, depending on the specific combination of these variables.

The optimal conditions identified through RSM-BBD were as follows: a mass of oil of 11.14 g, a NaOH to oil ratio of 0.20 g/g, and a heating time of 25.70 minutes. Under these conditions, the yield of solid alcohol was 87.0923%, which is very close to the highest observed yield. The desirability level for this optimization was calculated to be 0.911, indicating a high level of process efficiency. These findings suggest that the selected conditions represent an optimal balance within the experimental constraints, enabling a high yield of solid alcohol while efficiently utilizing materials and time.

The results from the optimization process align with previous research on the synthesis of solid alcohol, particularly in highlighting the importance of maintaining specific ratios and conditions to achieve high yields. Studies such as those by Xiong et al. (2019) [7] and Tan et al. (2019) [11] have similarly emphasized the critical role of the NaOH to oil ratio and heating time in determining the efficiency and outcome of the synthesis process. However, this study advances their work by offering a more precise and systematic optimization using RSM-BBD, which not only identifies the optimal conditions but also quantifies the desirability of these conditions, thereby providing a more comprehensive understanding of the synthesis process.

In contrast to earlier studies that often relied on trial-and-error methods or simpler experimental designs, this study's use of RSM-BBD offers a more sophisticated approach to optimization. This method enables the exploration of interactions between variables and the identification of quadratic effects that might not be evident in less complex experimental setups. As a result, this study provides a more comprehensive understanding of how the mass of oil, NaOH to oil ratio, and heating time interact to influence yield, leading to a more efficient and targeted approach to process optimization.

The determination of the optimal conditions for solid alcohol synthesis carries significant scientific and practical implications. Scientifically, the use of RSM-BBD to optimize the synthesis process offers a robust and reliable method for identifying the most efficient conditions, thereby contributing to the broader body of knowledge in biofuel production and waste management. This study illustrates the effectiveness of advanced statistical techniques in fine-tuning complex chemical processes, providing insights that could be applied to other areas of research and industrial production.

Practically, achieving high yields of solid alcohol with minimal waste of materials and time is essential for the scalability and economic viability of this process. The optimization results indicate that industries can adopt these conditions to maximize production efficiency, reduce costs, and minimize environmental impact. The identified optimal conditions not only enhance yield but also ensure that the process can be scaled up without compromising quality or efficiency.

Moreover, the high desirability level associated with the optimal conditions suggests that this process is well-suited for industrial application, offering a sustainable and cost-effective solution for converting waste cooking oil into a valuable fuel source. This has the potential to significantly contribute to both energy security and environmental sustainability, especially in regions where waste cooking oil is abundant and disposal options are limited. In conclusion, the findings of this study provide a strong foundation for the practical application of solid alcohol synthesis from S-WCO, demonstrating both the scientific rigor of the optimization process and its potential for real-world impact.

Table 1: Experimental results for the optimization of solid alcohol synthesis from Supernatant-Waste Cooking Oil (S-WCO)

Run	Mass of Oil (g)	NaOH to Oil Ratio (g/g)	Heating Time (min)	Yield (%)
1	5	0.100	30	82.7254
2	10	0.175	30	86.4137
3	10	0.250	20	86.8239
4	10	0.175	30	86.9288
5	10	0.175	30	87.1343
6	5	0.250	30	83.3615
7	15	0.250	30	84.0748
8	5	0.175	40	81.1964
9	15	0.100	30	85.4339
10	5	0.175	20	83.1574
11	10	0.100	40	81.8924
12	10	0.100	20	83.6144
13	10	0.175	30	87.6717
14	15	0.175	40	82.0439
15	15	0.175	20	85.5751
16	10	0.175	30	85.0089
17	10	0.250	40	83.4806

Table 2: Analysis of variance for the fitted model in the synthesis of solid alcohol from Supernatant-Waste Cooking Oil (S-WCO) [Note: * = significant]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	58.31	9	6.48	5.71	0.0158*
A	5.59	1	5.59	4.93	0.0619
B	2.08	1	2.08	1.83	0.2182
C	13.93	1	13.93	12.28	0.0099*
A^2	14.35	1	14.35	12.65	0.0093*
B^2	3.31	1	3.31	2.92	0.1314
C^2	13.52	1	13.52	11.92	0.0106*
AB	1.00	1	1.00	0.88	0.3801
AC	0.62	1	0.62	0.54	0.4850
BC	0.66	1	0.66	0.58	0.4714
Residual	7.94	7	1.13		
Lack of Fit	3.84	3	1.28	1.25	0.4038
Pure Error	4.10	4	1.03		
Cor Total	66.25	16			

4. Conclusion

The optimization of solid alcohol synthesis from Supernatant-Waste Cooking Oil (S-WCO) using Response Surface Methodology (RSM) in conjunction with Box-Behnken Design (BBD) has demonstrated substantial potential for maximizing yield under controlled conditions. The study identified the optimal synthesis conditions as a mass of oil of 11.14 g, a NaOH to oil ratio of 0.20 g/g, and a heating time of 25.70 minutes. Under these conditions, the yield of solid alcohol reached 87.0923%, with a desirability level of 0.911, indicating a highly efficient process.

The findings confirm that the mass of oil, NaOH to oil ratio, and heating time are critical variables that must be precisely managed to achieve high yields. The study also underscores the effectiveness of using RSM-BBD for optimizing complex chemical processes, providing a robust model that can be applied in industrial settings to enhance the efficiency and scalability of solid alcohol production.

Overall, this research contributes significantly to the field of sustainable energy by presenting a viable method for converting waste cooking oil into a valuable fuel source, addressing both environmental and energy security challenges. The optimized synthesis process not only maximizes yield but also ensures the efficient use of resources, making it a promising option for large-scale implementation. Future research could focus on further refining the process, exploring alternative catalysts, and assessing the economic feasibility of scaling up the production of solid alcohol from waste cooking oil.

5. Acknowledgment

This work was supported by a grant from the Directorate of Research, Technology and Community Service - Directorate General of Higher Education, Research and Technology - Ministry of Education, Culture, Research and Technology in accordance with Research Contract Number: 080/E5/PG.02.00.PL/2024

6. References

[1] M.E. Ortner, W. Müller, I. Schneider, A. Bockreis, Environmental assessment of three different utilization paths of waste cooking oil from households, Resour Conserv Recycl 106 (2016) 59–67. https://doi.org/10.1016/j.resconrec.2015.11.007.

[2] Y. Hua, Research progress of higher alcohols as alternative fuels for compression ignition engines, Fuel 357 (2024) 129749. https://doi.org/10.1016/j.fuel.2023.129749.

[3] A.N. Baghani, S. Sadjadi, K. Yaghmaeian, A. Hossein Mahvi, M. Yunesian, R. Nabizadeh, Solid alcohol biofuel based on waste cooking oil: Preparation, properties, micromorphology, heating value optimization and its application as candle wax, Renew Energy 192 (2022) 617–630. https://doi.org/10.1016/j.renene.2022.04.100.

[4] W.H. Foo, S.S.N. Koay, S.R. Chia, W.Y. Chia, D.Y.Y. Tang, S. Nomanbhay, K.W. Chew, Recent advances in the conversion of waste cooking oil into value-added products: A review, Fuel 324 (2022) 124539. https://doi.org/10.1016/j.fuel.2022.124539.

[5] W.-T. Tsai, Mandatory Recycling of Waste Cooking Oil from Residential and Commercial Sectors in Taiwan, Resources 8 (2019) 38. https://doi.org/10.3390/resources8010038.

[6] N. Xu, H. Wang, H. Wang, M. Kazemi, E. Fini, Research progress on resource utilization of waste cooking oil in asphalt materials: A state-of-the-art review, J Clean Prod 385 (2023) 135427. https://doi.org/10.1016/j.jclepro.2022.135427.

[7] Y. Xiong, W. Miao, N. Wang, H. Chen, X. Wang, J. Wang, Q. Tan, S. Chen, Solid alcohol based on waste cooking oil: Synthesis, properties, micromorphology and simultaneous synthesis of biodiesel, Waste Manage 85 (2019) 295–303. https://doi.org/10.1016/j.wasman.2018.12.036.

[8] O.S. Ivashchuk, V.M. Atamanyuk, R.A. Chyzhovych, S.S. Kiiaieva, R.R. Zherebetskyi, I.B. Sobechko, Preparation of an alternate solid fuel from alcohol distillery stillage, Voprosy Khimii i Khimicheskoi Tekhnologii (2022) 54–59. https://doi.org/10.32434/0321-4095-2022-140-1-54-59.

[9] H. Dong, Y. Wei, S. Zhou, B. Li, H. Wang, Cracking of waste cooking oil in the presence of copper slag, Sustain Chem Pharm 22 (2021) 100482. https://doi.org/10.1016/j.scp.2021.100482.

[10] H.-Y. Xue, J.-R. Li, Y.-G. Liu, Q. Gao, X.-W. Wang, J.-W. Zhang, M. Tanokura, Y.-L. Xue, Optimization of the ultrafiltration-assisted extraction of Chinese yam polysaccharide using response surface methodology and its biological activity, Int J Biol Macromol 121 (2019) 1186–1193. https://doi.org/10.1016/j.ijbiomac.2018.10.126.

[11] Y.H. Tan, M.O. Abdullah, J. Kansedo, N.M. Mubarak, Y.S. Chan, C. Nolasco-Hipolito, Biodiesel production from used cooking oil using green solid catalyst derived from calcined fusion waste chicken and fish bones, Renew Energy 139 (2019) 696–706. https://doi.org/10.1016/j.renene.2019.02.110.

[12] R.F. Gunst, R.H. Myers, D.C. Montgomery, Response Surface Methodology: Process and Product Optimization Using Designed Experiments, Technometrics 38 (1996) 285–286. https://doi.org/10.2307/1270613.

[13] H. Li, L. Pordesimo, J. Weiss, High intensity ultrasound-assisted extraction of oil from soybeans, Food Res Int 37 (2004) 731–738. https://doi.org/10.1016/j.foodres.2004.02.016.

[14] A. Hapid, S. Zullaikah, M. Mahfud, A. Kawigraha, M.U. Azmi, I. Haryanto, H.P. Soewoto, A.W. Go, S. Assabumrungrat, Optimization of microwave-assisted roasting: Box-behnken design for oxidation of sulfide minerals and control of atmospheric sulfur in refractory gold ore pretreatment, Case Stud Chem Envir Eng 10 (2024) 100826. https://doi.org/10.1016/j.cscee.2024.100826.