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Comparative analysis of predictive models for *Tamarindus indica* waste briquettes higher heating value

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ABSTRACT

Utilising biomass waste as a renewable energy source has gained a lot of interest as a means of reducing reliance on fossil fuels. Among the many types of biomass, tamarind fruit peel (*Tamarindus indica*), which is commonly discarded, holds promise as a feedstock for briquette production due to its favorable combustion properties. In order to ascertain the higher heating value (HHV) of briquettes made from tamarind peel waste, this study employs proximate analysis, which takes into account the materials' moisture content, ash content, volatile matter, and fixed carbon. In this research, three models Wahid, Nhuchhen and Afzal, and Kieseler were comparatively analyzed to predict the HHV of tamarind peel briquettes. The study also explored the effects of particle size and binder ratio on briquette performance, specifically on HHV and combustion properties. Tamarind peel was processed into different powder sizes, mixed with varying binder ratios, and formed into briquettes. The three predictive models were statistically evaluated using R2, the Bayesian information criterion (BIC), and the akaike information criterion (AIC) after the briquettes were proximally analysed. With an R^2 of 0.96, the Wahid model showed the highest prediction accuracy, followed by Nhuchhen (0.93) and Kieseler (0.78), according to the data. Wahid's model also had the lowest AIC (45.3) and BIC (47.1), indicating it is the most efficient model for predicting the HHV of tamarind peel briquettes. According to the study, the best combinations for improved briquette performance were determined when particle size and binder ratio were found to have a substantial impact on the combustion characteristics. By turning leftover tamarind peel into a renewable energy source, this study promotes environmentally friendly waste management while also fostering energy innovation. The findings provide valuable insights into the optimization of biomass briquette production and highlight the potential of tamarind peel as an underutilized biomass resource.

Keywords: briquettes, tamarind fruit peel waste, higher heating value, combustion efficiency, binder ratio, powder size.

INTRODUCTION

One of the most important issues in the global effort to lessen reliance on fossil fuels is the management of biomass waste as a renewable energy source. Biomass, which includes a variety of organic waste products, such as fruit and agricultural waste, has a lot of potential for use as an alternative fuel. One of the promising methods for biomass utilization is the production of briquettes, which involve compressing biomass materials to increase energy density and enhance combustion efficiency. Among the various potential raw materials for briquette production, tamarind fruit peel waste (*Tamarindus indica*) stands out as a viable feedstock.

Tamarindus indica is a tropical plant that is widely farmed, particularly in nations like Indonesia, where the fruit skin is sometimes thrown away as waste after the edible pulp has been removed. However, because of its natural energy content and advantageous combustion properties, this fruit peel waste has significant promise as a biomass briquette material. The higher heating value (HHV), a crucial measure that indicates the total energy available in the biomass after complete burning, must be determined scientifically in order to maximise the use of this waste. Predicting the higher heating value, which is crucial for assessing a material's energy potential, depends on proximate analysis, which measures the biomass's moisture content, ash content, volatile matter, and fixed carbon. The energy release and combustion efficiency throughout the burning process are directly impacted by these proximate analysis parameters.

The use of leftover tamarind fruit peel as a feedstock for the manufacturing of biomass briquettes is a significant breakthrough of this study. While many agricultural leftovers have been thoroughly researched for the production of briquettes, tamarind peel has not received as much attention, despite being widely available in tropical areas. This study promotes sustainable waste management and renewable energy initiatives by turning this garbage into a renewable energy source. These programs are particularly pertinent in regions where tamarind is commonly farmed. This approach offers an environmentally sustainable energy source in addition to lessening the environmental impact of trash disposal.

While most previous studies have focused on applying a single model for predicting the HHV of biomass, this research takes a comparative approach by examining three distinct modell Wahid (2017), Nhuchhen and Afzal (2017), and Kieseler (2013) to assess their accuracy and suitability for tamarind peel biomass briquettes. Each model incorporates unique variables and methodologies derived from proximate analysis data, and by evaluating their performance side by side, this study aims to identify which model is best suited for tamarind peel briquettes. This comparative analysis not only provides a more in-depth understanding of how different predictive models behave but also addresses a gap in the existing literature concerning the empirical evaluation of HHV prediction models for unconventional biomass sources like tamarind peel.

The research introduces another innovation by investigating the impact of particle size and tapioca binder ratio on the briquette's combustion properties and HHV. Both of these factors play a crucial role in the physical and thermal characteristics of briquettes, yet their effects have been underexplored in the context of tamarind peel biomass. By systematically varying the particle size and binder ratio, this study provides new insights into how these parameters influence the efficiency and energy content of briquettes, thereby contributing to the body of knowledge on biomass briquette optimization. The findings, particularly on model performance and optimization of powder size and binder ratio, can be transferable to other biomass types with similar combustion characteristics, such as those with moderate energy content and specific moisture and ash profiles. However, each biomass type may differ in critical parameters like fixed carbon and volatile matter, which influence HHV. Testing similar models on other biomass types would clarify their broader applicability. The primary drawbacks of using biomass as a source of energy Pre-treatment can address low energy density, high moisture content, irregular shape, low carbon content, and high tar content. To enhance calorific value, the ideal torrefaction conditions are discovered at 300 °C for 20 minutes (Dethan et al., 2024a).

Practically speaking, it encourages the creation of renewable energy technology that can be used in places with limited access to traditional energy sources, such as rural and peri-urban areas. This study encourages circular economies and sustainable energy techniques that meet local energy needs while reducing environmental waste by using locally accessible waste materials like tamarind peel. Because biomass briquettes burn cleaner than fossil fuels, the research also advances the larger objective of lowering greenhouse gas emissions.

The comparative analysis of three HHV prediction models provides a critical evaluation of their applicability, filling a gap in the current literature on biomass energy. Many studies on biomass briquetting prioritize common agricultural residues (e.g., rice husks, coconut shells), but this study expands the scope to fruit peel waste, aligning with sustainability goals by exploring less conventional materials. This contribution supports a broader understanding of biomass diversity in briquette production. Fruit peels, such as those from peach palm and sugarcane, can be effectively used in biocomposite production, demonstrating their potential as a biomass source (Enriquez-Medina et al., 2024). The incorporation of fruit peel waste can improve the mechanical properties of briquettes, as seen in studies where organic binders from cassava and matooke peelings enhanced the thermal stability and energy density of rice husk biochar briquettes (Lubwama et al., 2024). Utilizing fruit peel waste reduces the environmental impact associated with agricultural residues, promoting a circular economy by repurposing waste materials. The integration of diverse biomass sources, including fruit peels, can mitigate the challenges of waste disposal and contribute to sustainable energy solutions (Zhang et al., 2024). Finally, the research's focus on optimizing briquette properties through particle size and binder ratio experimentation offers new insights into the practical aspects of biomass briquette production. These contributions collectively underscore the importance of the research in advancing both scientific understanding and practical applications in the field of renewable energy.

METHODS

The materials and equipment used in this study include tamarind peel, tapioca flour as a binder, and water for the mixing and briquette-forming process. The equipment used is a grinding machine, tyler sieve, and digital scales to measure the weight of raw materials and binders accurately. In addition, a briquette press machine is used to apply pressure and form briquettes, along with a drying oven. Proximate analysis equipment is used to determine the water content, ash content, volatile substances, and fixed carbon in briquettes. The investigation was carried out in the agricultural product technology laboratory of Kupang State Agricultural Polytechnic and the exact laboratory of Artha Wacana Christian University. A grinder was used to grind the dried tamarind peel into a variety of powder sizes. To obtain powder in the size range of 20 to 60 mesh (x1), the resultant powder was subsequently sieved using a sieve. Briquettes are made by mixing tamarind peel powder with a binder at a predetermined ratio, usually ranging from 4% to 8% (x2). Water is added to the mixture, which is then mixed thoroughly to ensure homogeneity. Then put the material into the briquette press machine to form briquettes.

The briquettes are then dried in an oven at a controlled temperature until the desired moisture content is achieved. Following drying, the briquettes are tested using proximate analysis tools to determine proximate characteristics such as moisture content, ash content, volatile matter, and fixed carbon. For biomass briquettes, ASTM proximate analysis employs ASTM, specifically ASTM E871 for determining the moisture content of particulate wood fuel, ASTM E1755 for determining the amount of ash in biomass, and ASTM E872 for determining volatile matter. Carbon fixed (%) = content of moisture (%), the percentage of volatile matter content of ash (%).

A statistical analysis was performed to evaluate the appropriateness of Wahid's suggested models (Wahid et al., 2017) in Equation 1, Nhuchhen (Nhuchhen and Afzal, 2017) in Equation 2, and Kieseler (Kieseler et al., 2013) in Equation 3 using R square (R^2). Two model selection criteria, the Bayesian information criterion (BIC) and the Akaike information criterion (AIC), were contrasted and assessed (Kuha, 2004). They clarify the reasons for their estimations of the two distinct goal numbers, and their accuracy in doing so is evaluated. Despite having distinct bases, there are some commonalities between the two statistics. For instance, their penalty rules can be interpreted similarly. The behaviour of the selection criteria for an appropriate model for observational data is analysed using simulated data and is further demonstrated by analysing two popular social mobility data sets. It is suggested that combining AIC and BIC can yield valuable information for model selection; in particular, the recommended model should be found as closely as feasible based on these two criteria.

Wahid model equation:

$$HHV = 15.85 + 1.93\frac{FC}{VM} + 0.04\frac{VM}{ASH} + + 0.14\frac{ASH}{FC} + 0.02t + 0.01T \tag{1}$$

Nhuchhen model equation:

$$HHV = 0.1846\, x\, VM + 0.35\, x\, FC \tag{2}$$

Kieseler model equation:

$$HHV = 0.4108\, x\, FC + 0.19\, x\, VM \tag{3}$$

RESULT AND DISCUSSIONS

The experimental findings from a study examining the impact of different powder sizes and binder ratios on the thermochemical characteristics of briquettes manufactured from leftover tamarind fruit peel are summarised in Table 1. With information on the precise parameters used and the resulting measurements of MC, ash content,

Table 1. Experimental results on HHV of tamarind fruit peel waste briquettes based on the Wahid, Nhuchhen, and Kieseler models

Std	Run	x_1: Powder size	x_2: Binder ratio	MC	Ash	VM	FC	Wahid	Nhuchhen	Kieseler
		Mesh	%	%	%	%	%	MJ/kg	MJ/kg	MJ/kg
5	1	60	4	5.74	5.71	66.14	22.41	20.11	21.88	14.42
13	2	40	9	6.03	6.78	62.28	24.91	20.28	22.13	13.68
6	3	12	6	5.41	6.01	79.88	8.7	17.81	18.90	13.27
12	4	40	6	6.72	6.72	64.72	21.84	19.65	21.35	14.63
8	5	40	3	5.41	6.08	75.34	13.17	18.55	19.85	15.41
7	6	40	6	6.77	6.74	64.54	21.95	19.65	21.36	14.58
11	7	40	6	6.72	6.72	64.38	22.18	19.70	21.42	14.31
3	8	20	4	5.35	6.15	79.15	9.35	17.91	19.02	13.37
1	9	20	8	5.64	6.38	76.24	11.74	18.21	19.43	13.32
9	10	70	6	6.24	5.74	61.47	26.55	20.71	22.67	14.54
10	11	60	8	5.95	6.65	61.62	25.78	20.46	22.37	14.38
2	12	40	6	6.77	6.73	64.48	22.02	19.67	21.37	14.62
4	13	40	6	6.71	6.71	64.34	22.24	19.72	21.44	15.01

VM, FC, and HHV, expressed in MJ/kg, each row represents a distinct experimental run.

The surface plots of the three models Wahid, Nhuchhen, and Kieseler illustrate the relationship between two critical input variables, powder size and binder ratio, and their effect on the predicted performance of briquettes, likely in terms of HHV or similar parameters. Each model offers a distinct perspective on how these two factors influence the briquette's performance, with different response surfaces reflecting varying degrees of sensitivity to changes in the input variables (Fig. 1). These models are crucial for optimizing briquette production, allowing for the identification of ideal combinations of powder size and binder ratio that maximize performance, as predicted by each empirical equation. Briquettes with the ideal 60-mesh particle size and 5% binder ratio have the following characteristics: a density of 0.57 g/cm³, a calorific value of 15.91 MJ/kg, a total phenol content of 0.95 mgGAE/g, an ash content of 2.28%, a moisture content of 3.37%, a volatile matter of 14.83%, and a fixed carbon of 79.53% (Dethan & Lalel, 2024). Water absorption stays below 1% (0.65–0.675%), the HHV prediction reaches 29.0750 MJ/kg, and the color of the kesambi leaves and pruning changes from brown to black

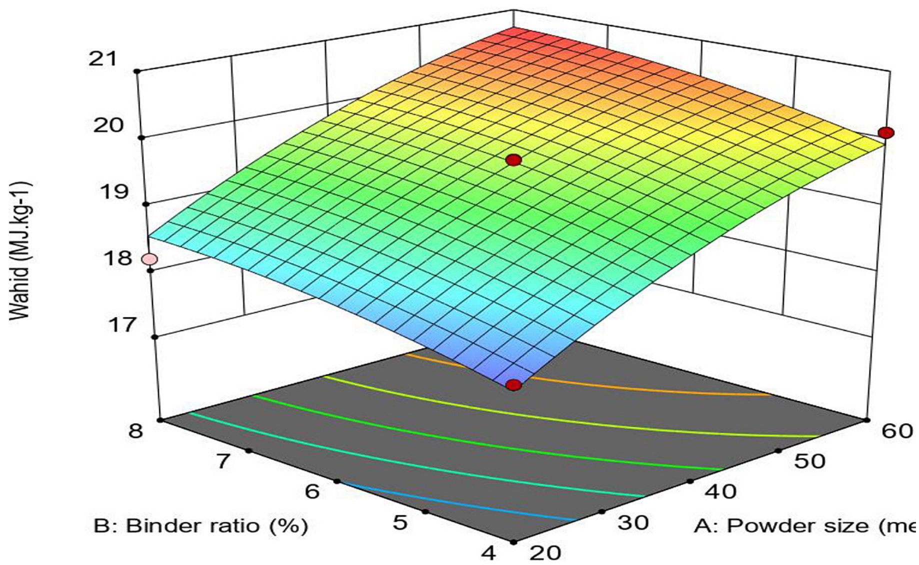

Figure 1. Plot surface of Wahid model

as the residence duration grows. The yield percentage also decreases and reaches its lowest at 20 minutes (Dethan et al., 2024b).

In all three models, the binder ratio and powder size play significant roles in determining the response, but the magnitude and nature of their effects vary across the models. Wahid's model demonstrates a relatively balanced effect of both variables, while Nhuchhen's model (Fig. 2) places greater emphasis on the increase in performance with higher binder ratios. Kieseler's model (Fig. 3), in contrast, highlights the importance of both powder size and binder ratio but shows a smoother, more gradual increase in the response. These surface plots provide valuable insights into how different models predict the briquette performance based on proximate analysis, offering a comparative view of optimization potential for briquette manufacturing processes.

Table 2 presents a comparative analysis of three predictive models Wahid, Nhuchhen, and Kieseler in terms of their statistical performance metrics, including R^2, AIC, and BIC. The R^2 value indicates the proportion of variance explained by each model, providing a measure of the model's accuracy in predicting the target variable. A higher R^2 value signifies better fit, with Wahid's model achieving the highest value (0.96), followed by Nhuchhen (0.93) and Kieseler (0.78), implying that the Wahid model offers the most accurate predictions among the three.

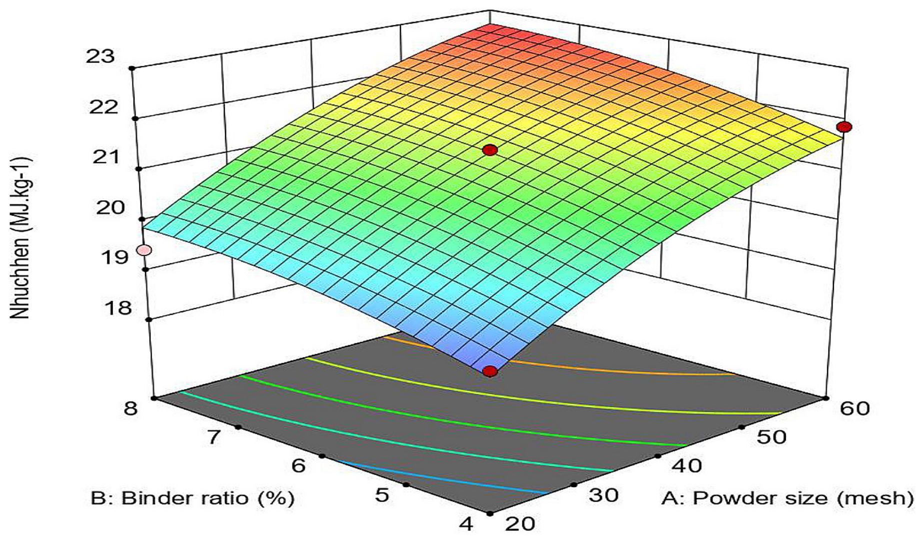

Figure 2. Plot surface of Nhuchhen model

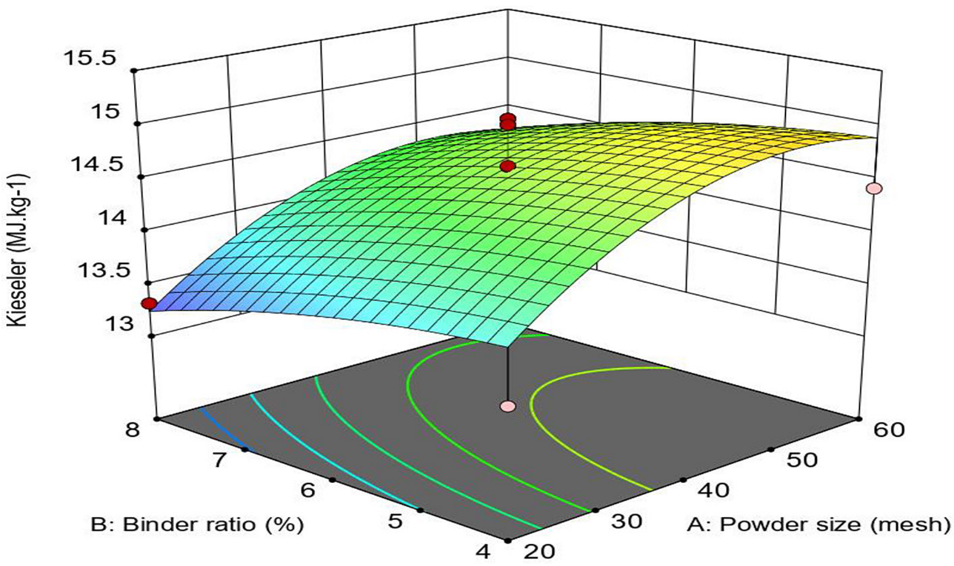

Figure 3. Plot surface of Kieseler model

Table 2. Comparative R^2, AIC, and BIC Analysis of Wahid, Nhuchhen, and Kieseler models

Std	Run	x_1: Powder size	x_2: Binder ratio	MC	Ash	VM	FC	Wahid	Nhuchhen	Kieseler
		Mesh	%	%	%	%	%	MJ/kg	MJ/kg	MJ/kg
5	1	60	4	5.74	5.71	66.14	22.41	20.11	21.88	14.42
13	2	40	9	6.03	6.78	62.28	24.91	20.28	22.13	13.68
6	3	12	6	5.41	6.01	79.88	8.7	17.81	18.90	13.27
12	4	40	6	6.72	6.72	64.72	21.84	19.65	21.35	14.63
8	5	40	3	5.41	6.08	75.34	13.17	18.55	19.85	15.41
7	6	40	6	6.77	6.74	64.54	21.95	19.65	21.36	14.58
11	7	40	6	6.72	6.72	64.38	22.18	19.70	21.42	14.31
3	8	20	4	5.35	6.15	79.15	9.35	17.91	19.02	13.37
1	9	20	8	5.64	6.38	76.24	11.74	18.21	19.43	13.32
9	10	70	6	6.24	5.74	61.47	26.55	20.71	22.67	14.54
10	11	60	8	5.95	6.65	61.62	25.78	20.46	22.37	14.38
2	12	40	6	6.77	6.73	64.48	22.02	19.67	21.37	14.62
4	13	40	6	6.71	6.71	64.34	22.24	19.72	21.44	15.01

The AIC and BIC criteria are used to assess the trade-off between model complexity and goodness of fit. Lower values for these criteria suggest a more efficient model in terms of balancing accuracy and parsimony. In this case, Wahid's model not only has the highest R^2 but also the lowest AIC and BIC values (45.3 and 47.1, respectively), indicating it strikes the best balance between complexity and predictive power. Nhuchhen's model, while slightly less accurate in terms of R^2, has higher AIC and BIC values, suggesting it is relatively less efficient. Kieseler's model, with the lowest R^2 and higher information criterion values, is the least optimal of the three models for predictive purposes.

Wahid model

With an R^2 value of 0.96, the Wahid model is the most reliable of the three. It shows that the independent variables of binder ratio and powder size account for 96% of the variability in the dependent variable. This high R^2 indicates that the model is probably accurately capturing the underlying relationship and that it fits the data well.

$$Wahid = 19.67 + 1.07x_1 1 + 0.38x_2 + \\ + 0.01x_1x_2 - 0.26x_1^2 - 0.15x_2^2 \quad (4)$$

The intercept indicates the expected value of the dependent variable when both powder size and binder ratio are zero. While this may not be practically meaningful, it sets a baseline for the predictions. This positive coefficient suggests that for each unit increase in powder size, the dependent variable increases by 1.07 units, assuming binder ratio is held constant. This strong influence indicates that powder size is a key predictor. The coefficient x2 (binder ratio) (0.38): shows that binder ratio also has a positive effect, though it is less pronounced than powder size. An increase in binder ratio by one unit results in an increase of 0.38 in the dependent variable.

The positive interaction term indicates that the effect of powder size on the dependent variable slightly increases as binder ratio increases, suggesting that these variables may complement each other in their effect of briquettes. The negative coefficients for the quadratic terms indicate diminishing returns; as powder size and binder ratio increase, their respective contributions to the dependent variable eventually decline. This reflects a common pattern in many natural phenomena.

The combination of powder size and binder ratio significantly impacts briquette properties, with the dependent variable increasing with increasing binder ratio. This suggests a complementary relationship between these variables. However, the negative coefficient for the quadratic term highlights diminishing returns, where further increases in powder size and binder ratio lead to diminishing contributions to the dependent variable. Higher binder ratios enhance the impact of smaller powder sizes on briquette strength (Rahman et al., 2023). Optimal binder ratios (e.g., 12.71% bentonite) yield maximum compressive strength (de Melo Silva Cheloni et al., 2024). Increased powder size beyond a certain point results in lower compressive strength (Setter et al., 2021). The addition of binders improved strength up to a threshold, after which benefits decline (Bao et al., 2020).

A lower AIC (45.3) suggests a better fit when considering the complexity of the model. Wahid's low AIC reinforces its position as the most effective model. Similarly, the BIC (47.1) also supports the choice of the Wahid model due to its relatively low value, indicating that it balances fit and complexity well. A lower AIC, such as 45.3 for the Wahid model, indicates a superior fit, while the BIC value of 47.1 further supports this model's effectiveness. These criteria are particularly relevant in mechanistic models, where simplicity and fit are crucial (Harbecke et al., 2024). AIC and BIC are widely used for model selection across various fields, including item response theory and reliability modeling (Sun et al., 2022). AIC is sensitive to model complexity, often favoring simpler models (Sen and Cohen, 2024). BIC tends to perform better in identifying the correct model as complexity increases (Sen and Cohen, 2024). Both criteria are applicable in Bayesian contexts, although new indices are being developed for complex data (Lu and Zhang, 2022). Despite their utility, some studies suggest that AIC and BIC may not be sufficient for all model types, indicating a need for alternative approaches in certain scenarios (Harbecke et al., 2024). The Wahid model, due to its strong predictive capability, can be a valuable tool for decision-making in contexts where understanding the relationship between powder size and binder ratio is critical. Whether in fields like economics, environmental studies, or social sciences, leveraging this model could yield significant insights.

Nhuchhen model

With an R^2 of 0.93, the Nhuchhen model accounts for 93% of the variance in the dependent variable. Despite being a high number, this value is less than that of the Wahid model, indicating that some variability cannot be explained.

$$Nhuchhen = 21.38 + 1.39x_1 + 0.51x_2 + \\ + 0.02x_1x_2 - 0.37x_1^2 - 0.22x_2^2 \quad (5)$$

A small positive interaction term suggests a minor synergistic effect, indicating that while increasing powder size and binder ratio can enhance certain properties, the impact is less significant than in the Wahid model. The combination of different particle sizes can lead to improved mechanical properties, as seen in studies on ultra-high-performance concrete and composite cementitious materials, where optimal particle size distributions enhanced strength and durability (Hao et al., 2022; Soliman et al., 2024). In binder jetting, the relative sizes of powder particles and binder droplets significantly influence part density and mechanical strength, with smaller particles often yielding better results (Rahman et al., 2023). Negative coefficients in the models indicate diminishing returns, where increases in powder size and binder ratio lead to reduced rates of improvement in mechanical properties (Manotham and Tesavibul, 2022; Roberts et al., 2020). The creation of biomass briquettes from kesambi twigs and candlenut shell charcoal shows that adding more of the former improves the briquette's characteristics. The Nhuchhen model, which has an R^2 of 0.93, predicts a calorific value of more than 19 MJ/kg, establishing these briquettes as a sustainable substitute for traditional fuels (Dethan, 2024).

The comparison of the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) indicates that the Wahid model is a better fit than the AIC model, as evidenced by the lower BIC value. AIC is widely used for model selection, but it can sometimes lead to overfitting, especially in complex models (Jansen, 2024; Kitagawa, 2023). In contrast, BIC tends to penalize model complexity more heavily, making it a more reliable choice in many scenarios (Muela and López-Martín, 2023; Sen and Cohen, 2024). This is particularly relevant in high-dimensional settings where the risk of false positives is significant. AIC (50.2) is higher than BIC (52), suggesting a poorer fit for the AIC model. BIC's lower value indicates a preference for the Wahid model, aligning with findings that BIC performs better in complex model scenarios (Sen and Cohen, 2024). The reliability of information criteria can vary based on sample size and model complexity (Muela and López-Martín, 2023). AIC's performance can diminish in high-dimensional contexts, leading to potential misestimations (Jansen, 2024). BIC is generally favored for its robustness against overfitting (Sen and Cohen, 2024). While the Wahid model is preferred based on AIC and BIC, it is essential to consider the context and specific characteristics of the data, as different models may perform

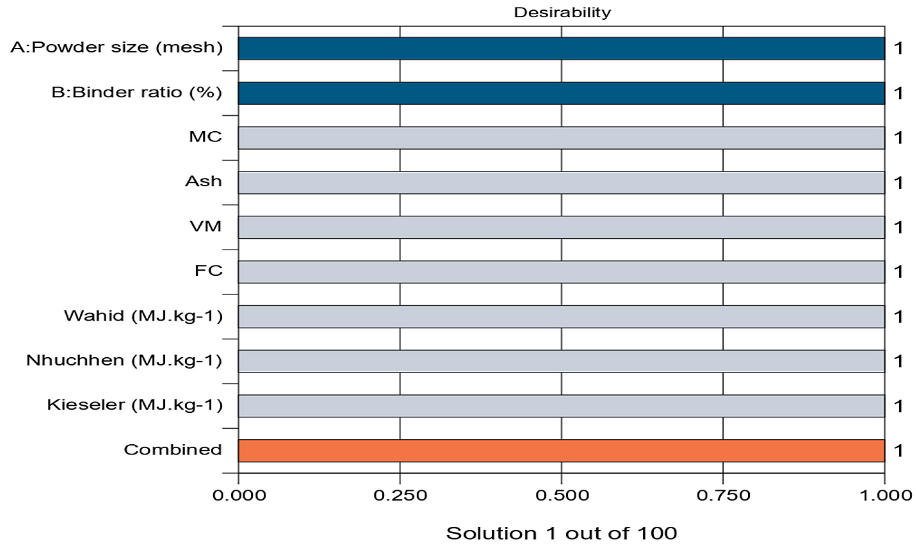

Figure 4. Desirability plot for optimizing factors in torrefied Kesambi leaf briquette production

better under varying conditions, highlighting the importance of comprehensive model evaluation. The Nhuchhen model, while slightly less effective than Wahid, still offers substantial explanatory power. It may be particularly useful in scenarios where the relationship between powder size and binder ratio is complex but not as dominant as in the Wahid context. Researchers should consider this model for investigations where the effects of both variables are critical but may not interact as strongly.

Kieseler model

With an R^2 of 0.78, the Kieseler model explains only 78% of the variability in the dependent variable, indicating a weaker fit compared to the other two models. This suggests that additional variables may be influencing the dependent variable, or that the relationships are more complex.

$$Kieseler = 14.62 + 0.51x_1 - 0.32x_2 + \\ + 0.01x_1x_2 - 0.44x_1^2 - 0.11x_2^2 \quad (6)$$

Although the AIC and BIC are frequently employed for model selection, depending on the situation, their efficacy might vary greatly. The AIC value of 48.7 suggests a reasonable fit, yet it is higher than those of the Wahid and Nhuchhen models, indicating a less optimal fit. The BIC value of 50.5 further supports this conclusion, as it typically imposes a stronger penalty for model complexity, making it more conservative in model selection (Brewer et al., 2016; Sen and Cohen, 2024). AIC is often favored for its minimax-rate optimality in estimating regression functions (Yang, 2005). BIC is consistent in selecting the true model, especially in the presence of unobserved heterogeneity (Brewer et al., 2016). Simulation studies show that AIC performs well with low heterogeneity, while BIC excels with high heterogeneity (Brewer et al., 2016). The performance of these criteria can be influenced by sample size and model complexity (Sen and Cohen, 2024). Despite their utility, reliance on a single criterion may not yield universally optimal results, suggesting the need for a more nuanced approach to model selection (Sen and Bradshaw, 2017). The Kieseler model, while offering some insights, may not be suitable for applications requiring high predictive accuracy. It highlights the complexity of relationships between powder size and binder ratio but also suggests that additional factors may need to be included for a more comprehensive understanding. The desirability plot in Figure 4 illustrates how several parameters are optimised to arrive at the best possible solution in a model, most likely pertaining to the manufacturing of torrefied Kesambi leaf briquettes. The models displayed most likely reflect several approaches to forecasting the result, perhaps the briquettes' calorific value. The plot also represents the combined desirability score across all factors, indicating the overall optimal solution. It demonstrates that all factors in the model contribute equally and optimally to achieving the best result for the torrefied Kesambi leaf briquettes under the given conditions.

CONCLUSIONS

In this study, the performance of three predictive models Wahid, Nhuchhen, and Kieseler was evaluated to optimize the production of torrefied Kesambi leaf briquettes based on two critical input variables: powder size and binder ratio. The surface plots from each model reveal different sensitivities to these variables, providing distinct insights into their roles in the briquette manufacturing process.

The Wahid model emerged as the most accurate and efficient, with an R^2 value of 0.96 and the lowest AIC and BIC scores, indicating strong predictive power and a balanced complexity. This model highlights the significant impact of powder size and binder ratio on briquette performance, with positive interaction effects and diminishing returns at higher levels of both factors. The model's robustness makes it a valuable tool for optimizing the briquette production process.

The Nhuchhen model also demonstrated strong predictive capabilities with an R^2 of 0.93. Despite being marginally less precise than the Wahid model, it provides insightful information, especially in situations when the relationship between powder size and binder ratio is not as strong. In comparison to the Wahid model, the model appears to be more complex, but its ability to balance complexity and fit is less effective, as indicated by the higher AIC and BIC values.

The Kieseler model had the lowest R^2 value of 0.78, indicating a weaker fit. This model may require the inclusion of additional variables to account for the variability in briquette performance. While it provides some insights, it is less suitable for applications requiring high predictive accuracy and may not be optimal for decision-making in briquette production.

Wahid model stands out as the most effective for predicting and optimizing briquette performance based on powder size and binder ratio. The results emphasize the importance of carefully selecting these input variables to maximize the quality and performance of torrefied Kesambi leaf briquettes. The desirability plot further underscores that all factors contribute optimally to the desired outcomes, confirming that the models can be used to guide the production process toward achieving the best possible briquette properties under given conditions.

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