

DEVELOPMENT AND FIELD APPLICATION OF PHYSICAL ADULTERATION INDEX FOR DETECTING RICE HUSK ADULTERATION IN RICE BRAN USED AS A FEED INGREDIENT

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ABSTRACT

Rice bran is widely used as a feed ingredient, but rice husk adulteration can compromise its quality. This study developed a Rice Bran Physical Adulteration Index (RBP AI) based on simple physical measurements and evaluated its potential for screening commercial rice bran. We prepared reference mixtures containing 0–100% rice husk at 2.5% intervals and obtained ten replicate measurements at each of 41 adulteration levels. We measured bulk density (BD), tapped density (TD), and angle of repose (AR), and subjected the mean values at each adulteration level to principal component analysis (PCA). We used the retained principal component to construct the RBP AI, then calibrated it against known rice husk proportions using linear regression. We then applied the index to 31 commercial rice bran samples collected from rice mills, traders, feed mills, and livestock farmers in South Sulawesi, Indonesia. Bulk density and TD increased progressively with increasing rice husk proportion, whereas AR decreased. The first principal component explained 98.433% of the total variance and yielded the equation $RBP AI = 0.337ZBD + 0.337ZTD - 0.335ZAR$. The RBP AI showed a strong linear relationship with rice husk proportion ($R^2 = 0.969$), with an apparent calibration mean absolute error (MAE) of 4.259 and root mean square error (RMSE) of 5.183 percentage points. Commercial samples exhibited substantial variation in RBP AI-derived adulteration estimates across supply-chain groups and sampling locations. These findings suggest that RBP AI can convert low-cost physical measurements into a practical preliminary screening tool for assessing rice bran quality. However, because rice husk content in the commercial samples was not independently verified, treat the field estimates as model-based indications and confirm them with appropriate analytical methods.

Keywords: Bulk density, Feed quality, Physical adulteration, Principal component analysis, Rice bran, Rice husk, Tapped density.

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1. INTRODUCTION

Rice bran is an important by-product of rice milling and is widely used as a feed ingredient because it supplies energy, protein, lipids, fiber, vitamins, and minerals at a relatively accessible cost (Bodie et al., 2019; Manlapig & Matsui, 2025; Aktar et al., 2026; Gul et al., 2026). Its availability is closely tied to the scale of rice production. Indonesia produced approximately 60.21 million tonnes of dry unhusked paddy in 2025, of which 5.47 million tonnes originated from South Sulawesi (BPS-Statistics Indonesia, 2026). This production base generates a substantial supply of milling by-products and supports the continued use of rice bran in livestock and poultry feeding.

However, the feeding value of commercial rice bran varies widely. Rice variety, milling system, and degree of milling can influence the distribution of protein, fat, fiber, minerals, and other constituents in the resulting bran fraction (Kalpanadevi et al., 2018; Oppong Siaw, 2023; Kabir et al., 2024). Its physical properties may continue to change after milling, as storage duration, moisture accumulation, packaging, and handling can alter bulk density, tapped density, and material stability (Ridla et al., 2023a). Rice mills in South Sulawesi have also shown variation, with bulk density, tapped density, and estimated nutrient contents differing by sampling location and milling source

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(Ridla et al., 2023b). Quality may decline further when rice bran is mixed with lower-value materials. Rice husk is particularly relevant because milling produces it alongside bran, and it can be ground and incorporated into the product.

Experimental evidence shows that increasing rice husk content alters the nutritional composition of rice bran. Adding husk increases ash, crude fiber, acid detergent fiber, cellulose, and lignin while reducing crude protein, fat, and other nutritionally valuable fractions (Maesaroh et al., 2023; Rusyidi et al., 2023). These changes dilute the material's feeding value and may compromise feed-formulation accuracy. Their functional consequences have also been demonstrated under *in vitro* conditions, where rice husk substitution reduced dry matter and organic matter digestibility, potential gas production, and the rate of ruminal gas production. A significant reduction in dry matter digestibility was detected at a rice husk substitution level of 10% (Fidriyanto et al., 2020). For farmers and feed manufacturers, purchasing adulterated rice bran can therefore result in lower nutrient delivery relative to the amount of feed purchased.

Chemical and fiber analyses can reveal compositional changes associated with rice husk addition and remain useful for confirming rice bran nutritional quality (Maesaroh et al., 2023; Rusyidi et al., 2023). Researchers have also explored several alternative approaches for faster detection. Phloroglucinol-assisted microscopy and color analysis use reactions in lignified husk tissues to distinguish rice husk from rice bran (Anitha et al., 2022; Hernaman et al., 2024), while image analysis combined with a convolutional neural network has been examined to classify adulterated samples (Albarki et al., 2023). Other studies have investigated ultrasonic wave attenuation and near-infrared reflectance spectra as indicators of rice husk addition (Bhagaspati et al., 2021; Damela et al., 2024). These approaches demonstrate growing interest in rapid rice bran authentication, although their routine use may depend on access to reagents, imaging protocols, spectral instruments, or model-specific calibration. A simpler preliminary test remains valuable for purchasing, receiving, and field inspection, especially where laboratory and instrumental facilities are limited.

The physical behavior of a granular feed material can support such screening. Bulk density describes the mass accommodated within a given bulk volume, while tapped density reflects particle rearrangement and consolidation following repeated tapping. Angle of repose relates to interparticle friction, resistance to movement, and flow behavior. Studies across a range of feed ingredients have shown that angle of repose varies with compressibility, density, and chemical composition, indicating that these measurements describe related features of material behavior rather than isolated properties (Syamsu et al., 2015; Pekel et al., 2022). In rice bran, the addition of rice husk or other fibrous adulterants has produced measurable changes in bulk density, compact or tapped density, and angle of repose, although the direction and magnitude of the response have differed among materials and experimental procedures (Ridla et al., 2022; Alfaresi et al., 2023; Maesaroh et al., 2023).

Existing studies confirm that individual physical measurements can respond to the addition of rice husk or other fibrous adulterants, but researchers have generally evaluated and interpreted the variables separately (Ridla et al., 2022; Alfaresi et al., 2023; Elkatry et al., 2023; Maesaroh et al., 2023). This treatment may be less efficient when BD, TD, and AR describe overlapping changes within the same particle system. Their interrelationships provide a basis for constructing a composite measure that captures the dominant physical gradient associated with adulterant addition. A calibrated index may also offer a more direct operational interpretation than several measurements assessed independently. Evidence remains limited on developing such an index across a continuous rice husk gradient and applying it to commercial rice bran from multiple points in the feed supply chain.

This study developed a Rice Bran Physical Adulteration Index (RBP AI) by integrating bulk density, tapped density, and angle of repose measured in experimentally prepared rice bran–rice husk mixtures. The index was calibrated against known rice husk proportions and then applied to commercial rice bran collected from rice mills, traders, feed manufacturers, and livestock farmers in South Sulawesi. The field application aimed to examine variation in RBP AI-derived estimates and assess the index's feasibility as a rapid screening method. Because the actual rice husk content of the commercial samples was not independently determined, these estimates were treated as indications of physical similarity to the experimental mixtures rather than definitive measurements of adulteration.

2. MATERIALS AND METHODS

2.1. Study Design

This study was conducted in two consecutive phases to develop and validate a Rice Bran Physical Adulteration Index (RBP AI) for estimating rice husk adulteration in rice bran used as a feed ingredient. The RBP AI is a novel composite index proposed in this study that integrates three measurable physical characteristics: bulk density (BD), tapped density (TD), and angle of repose (AR) into a single quantitative indicator of rice husk adulteration. The index was derived using principal component analysis (PCA), and its relationship with rice husk adulteration level was subsequently quantified through linear regression analysis.

Phase I focused on developing and calibrating the RBP AI using experimentally prepared rice bran reference samples with known proportions of rice husk. A total of 41 adulteration levels, ranging from 0 to 100% rice husk at

2.5% intervals, were evaluated. Each adulteration level was measured in ten replicates, resulting in 410 individual measurements. The ten replicate measurements at each adulteration level were summarized as mean values. Consequently, the dataset used for PCA and regression analysis consisted of 41 analytical observations, with each observation representing the mean physical characteristics of one adulteration level.

Phase II evaluated the practical applicability of the developed RBPAI under commercial conditions. Rice bran samples were collected from different stakeholders in the poultry feed supply chain, including rice mills, rice bran traders, feed manufacturers, and livestock farmers. The operational RBPAI equation and calibration model developed in Phase I were applied to these samples to estimate their physical similarity to experimentally prepared rice bran–rice husk mixtures. This phase was intended as a field application of the model rather than an independent validation, because the actual rice husk content of the commercial samples was not determined using an external reference method.

2.2. Phase I. Development of the Rice Bran Physical Adulteration Index (RBPAI) Model

2.2.1. Preparation of Experimentally Adulterated Rice Bran Samples: Reference samples were prepared following the rice bran–rice husk adulteration gradient described by Rusyidi et al. (2023), with modifications to accommodate the physical measurements used in the present study. The mixtures represented 41 adulteration levels ranging from 0 to 100% rice husk at 2.5% intervals. Each reference sample weighed 1 kg and was prepared by adjusting the proportions of rice bran and rice husk according to the desired adulteration level. For example, the 10% adulteration treatment consisted of 900 g rice bran and 100 g rice husk, whereas the 25% adulteration treatment consisted of 750 g rice bran and 250 g rice husk. Each adulteration level was prepared and measured in ten independent replicates, resulting in a total of 410 experimental observations.

2.2.2. Determination of Physical Characteristics: Three physical properties were measured for each sample, namely bulk density (BD), tapped density (TD), and angle of repose (AR).

Bulk Density: Bulk density was determined according to the standard gravimetric method and calculated as

$$BD = \frac{W}{V}$$

Where: BD = bulk density (kg/m³); W = sample weight (kg); V = uncompacted sample volume (m³)

Tapped Density: Tapped density was determined after repeated mechanical tapping until a constant volume was obtained and calculated as

$$TD = \frac{W}{V_t}$$

Where: TD = tapped density (kg/m³); W = sample weight (kg); V_t = tapped volume (m³)

Angle of Repose: The angle of repose was determined using the fixed funnel method and calculated as

$$AR = \tan^{-1} \left(\frac{H}{R} \right)$$

Where: AR = angle of repose (°), H = height of the conical pile (cm), R = radius of the pile (cm)

2.2.3. Data Preparation and Quality Assessment: The experimental dataset comprised 410 individual measurements obtained from 41 rice husk adulteration levels, with ten replicate measurements at each level. The data were initially examined for completeness, data-entry errors, missing values, duplicate records, and potentially implausible measurements.

For each adulteration level, the mean and standard deviation of bulk density, tapped density, and angle of repose were calculated from the ten replicate measurements. The mean values were subsequently used as analytical observations in PCA and regression analysis. Thus, the multivariate and calibration analyses were conducted using 41 observations corresponding to the 41 experimentally defined adulteration levels.

We calculated descriptive statistics, including the mean, standard deviation, minimum, and maximum, for each physical variable. The variability among replicate measurements was retained and presented descriptively to demonstrate the repeatability of the physical measurements at each adulteration level.

2.2.4. Principal Component Analysis: Principal component analysis was performed using the mean bulk density, tapped density, and angle of repose values obtained for each of the 41 adulteration levels. Before PCA, we evaluated the correlation matrix using the Kaiser–Meyer–Olkin measure of sampling adequacy, Bartlett's test of sphericity, individual measures of sampling adequacy, and variable communalities. Because the three physical variables were measured in different units and on different scales, we standardized them to z-scores before

component extraction. We initially considered components with eigenvalues greater than 1.0 for retention. We also considered the proportion of variance explained, the scree plot, component loadings, and the interpretability of the extracted components when determining how many components to retain. The physical variables were standardized using:

$$Z_i = \frac{X_i - \bar{X}_i}{SD_i}$$

Where: Z_i = standardized value, X_i = observed value, $\bar{X}_i$ = variable mean, SD_i = standard deviation

2.2.5. Development of the Rice Bran Physical Adulteration Index (RBPAI): The Rice Bran Physical Adulteration Index (RBPAI) was constructed from the first principal component (PC1) using the component score coefficients generated by PCA. The standardized RBPAI was calculated as:

$$RBPAI = a_1 Z_{BD} + a_2 Z_{TD} + a_3 Z_{AR}$$

Where: a_1, a_2, a_3 are the component score coefficients obtained from PCA.

For practical application, the standardized equation was transformed into an operational equation based on the original physical measurements:

$$RBPAI = b_0 + b_1 BD + b_2 TD + b_3 AR$$

Where: b_0 = intercept; b_1, b_2, b_3 = regression coefficients derived from the standardized PCA equation.

2.2.6. Development of the Regression Model: A simple linear regression model was developed to establish the quantitative relationship between the Rice Bran Physical Adulteration Index (RBPAI) and the known rice husk adulteration levels. The general regression model as below:

$$Y = \beta_0 + \beta_1 (RBPAI)$$

Where: Y = predicted rice husk adulteration (%); β_0 = intercept; β_1 = regression coefficient

2.2.7. Assessment of Regression Assumptions and Calibration Performance: The statistical adequacy of the linear calibration model was evaluated by examining the assumptions underlying simple linear regression. The relationship between RBPAI and the known rice husk adulteration level was examined for linearity. Diagnostic procedures evaluated model residuals for normality, homoscedasticity, and extreme or influential observations.

The F-test assessed the overall significance of the calibration model, while the coefficient of determination and adjusted coefficient of determination described the proportion of variation in rice husk adulteration explained by RBPAI. The standard error of the estimate described the dispersion of observed adulteration levels around the fitted regression line.

Calibration errors were summarized using mean absolute error, root mean square error, and mean prediction bias. These statistics were calculated by comparing the fitted adulteration values with the known adulteration levels used to construct the model. Therefore, MAE, RMSE, and prediction bias were interpreted as measures of apparent calibration performance rather than independent validation performance.

2.3. Phase II. Field Application of the Developed Rice Bran Physical Adulteration Index (RBPAI)

2.3.1. Collection of Commercial Rice Bran Samples: Commercial rice bran samples were collected from rice mills ($n=8$), rice bran traders ($n=8$), feed mills ($n=7$), and livestock farmers ($n=8$) located in South Sulawesi Province, Indonesia. Bulk density (BD), tapped density (TD) and angle of repose (AR) were measured using the same procedures described in Section 2.2.2.

2.3.2. Calculation of the Rice Bran Physical Adulteration Index (RBPAI): The developed operational RBPAI equation obtained in Phase I was applied to each commercial rice bran sample:

$$RBPAI = b_0 + b_1 (BD) + b_2 (TD) + b_3 (AR)$$

2.3.3. Prediction of Rice Husk Adulteration: Rice husk adulteration was estimated using the developed regression model:

$$\text{Predicted adulteration} = \beta_0 + \beta_1 (RBPAI)$$

Because rice husk adulteration cannot be negative, negative predictions were replaced by zero:

$$\text{Predicted adulteration} = 0, \text{ if Predicted} < 0$$

2.3.4. Evaluation of Practical Applicability: Predicted rice husk adulteration levels were summarized using descriptive statistics, including the mean, standard deviation, minimum, and maximum values. The practical applicability of the developed RBPAI was evaluated by comparing the predicted adulteration levels among stakeholder groups within the poultry feed supply chain. The field application aimed to demonstrate the RBPAI's potential as a rapid screening tool for identifying commercial rice bran samples with varying levels of suspected rice husk adulteration.

2.4. Statistical Analysis

The 10 replicate measurements at each rice husk adulteration level were summarized as mean $\pm$ standard deviation (SD). Mean bulk density (BD), tapped density (TD), and angle of repose (AR) values for the 41 adulteration levels served as the observations for correlation analysis, principal component analysis (PCA), and linear regression ($n = 41$). Pearson correlation analysis examined relationships among BD, TD, AR, and the known rice husk adulteration level. PCA was performed on standardized mean BD, TD, and AR values. The dataset's suitability for PCA was assessed using the Kaiser–Meyer–Olkin measure, Bartlett's test of sphericity, individual measures of sampling adequacy, and communalities.

Principal components were retained based on their eigenvalues, explained variance, and factor loadings and used to construct the Rice Bran Physical Adulteration Index (RBPAI). Simple linear regression was then used to model the relationship between RBPAI and the known rice husk adulteration level. Model adequacy was assessed through residual diagnostics for linearity, normality, homoscedasticity, and potentially influential observations. Calibration performance was summarized using the coefficient of determination (R^2), adjusted R^2 , F-statistic, standard error of the estimate, mean absolute error, root mean square error, and mean prediction bias.

For commercial samples, RBPAI scores and estimated rice husk adulteration levels were calculated using the equations developed in Phase I and summarized descriptively. These estimates characterized variation among samples and stakeholder groups but were not considered independently validated measurements of actual rice husk content.

Statistical analyses were performed using IBM SPSS Statistics version 24 (IBM Corp., Armonk, NY, USA). RBPAI scores and adulteration estimates for commercial samples were calculated using Microsoft Excel 365 (Microsoft Corporation, Redmond, WA, USA). Statistical significance was set at $P < 0.05$.

3. RESULTS

3.1. Physical Characteristics of Experimentally Adulterated Rice Bran

A total of 410 physical measurements were obtained across 41 experimentally defined rice husk adulteration levels ranging from 0 to 100% at 2.5% intervals, with ten replicate measurements at each level. The physical characteristics evaluated were bulk density (BD), tapped density (TD), and angle of repose (AR). Across the experimental gradient, mean BD increased from 299.20 kg/m³ in unadulterated rice bran to 405.00 kg/m³ at 100% rice husk, an absolute increase of 105.80 kg/m³ (35.36%). Mean TD similarly increased from 372.74 to 493.42 kg/m³, an increase of 120.68 kg/m³ (32.38%). In contrast, mean AR declined from 40.56° to 22.71°, a reduction of 17.85° (44.01%). At the midpoint of the experimental gradient (50% rice husk), the mean BD, TD, and AR values were 356.20 kg/m³, 428.32 kg/m³, and 33.69°, respectively. Although minor fluctuations occurred at several intermediate levels, the three variables showed clear directional responses to increasing rice husk proportion (Fig. 1).

The increase in BD and TD indicates that incorporating rice husk altered the packing and compaction characteristics of the mixtures. Under the experimental conditions, the mixtures occupied a smaller bulk volume per unit mass and consolidated more after tapping. The progressive reduction in AR was consistent with lower resistance to particle movement and improved apparent flowability. Nevertheless, AR should be interpreted as an indicator of flow behavior rather than a complete measure of flowability, which may also be influenced by particle size, shape, surface characteristics, and moisture content.

Variation among replicate measurements was relatively limited at most adulteration levels, as indicated by the generally small standard deviations. The absence of a marked increase in variability across the adulteration gradient suggests that the measurement procedures produced reasonably consistent results throughout the tested range. Visual inspection of the response patterns also showed gradual rather than abrupt changes in BD, TD, and AR as rice husk proportion increased.

3.2. Development of the Rice Bran Physical Adulteration Index

The three physical variables showed very strong intercorrelations. Bulk density (BD) and tapped density (TD) were positively correlated ($r = 0.989$), whereas both were negatively correlated with angle of repose (AR), with

coefficients of -0.970 and -0.971 , respectively (Table 1). Thus, the absolute correlation coefficients among the three variables ranged from 0.970 to 0.989 . The Kaiser–Meyer–Olkin measure of sampling adequacy was 0.723 , and Bartlett’s test of sphericity was statistically significant ($\chi^2 = 256.996$; $P < 0.001$). The individual measures of sampling adequacy ranged from 0.715 to 0.910 , while the communalities ranged from 0.976 to 0.989 . Collectively, these results indicated that the three physical variables shared substantial common variance and were suitable for integration using principal component analysis.

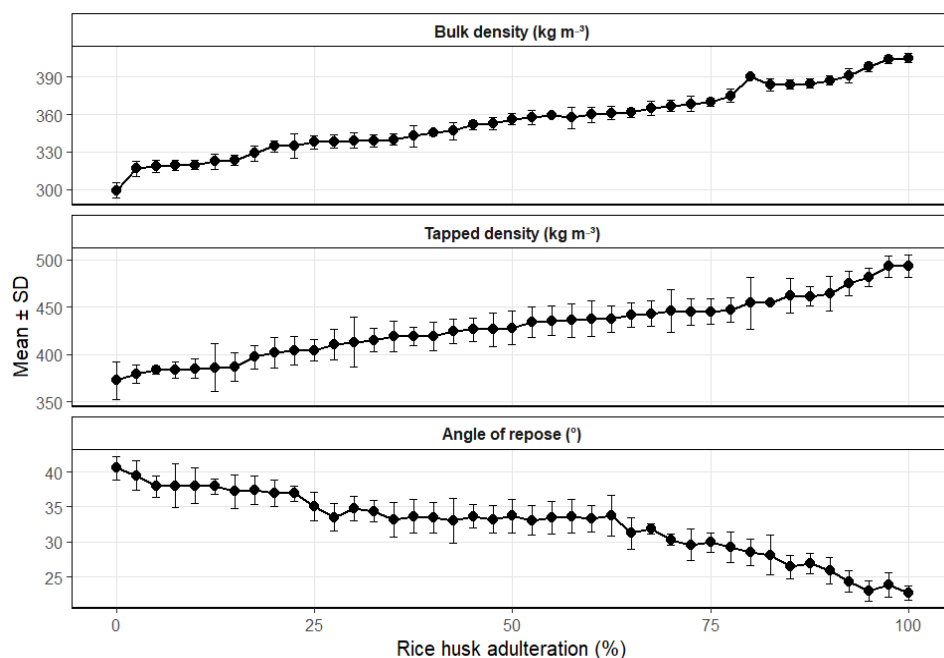


Fig. 1: Values (mean $\pm$ SD) of bulk density (BD), tapped density (TD), and angle of repose (AR) of experimentally prepared rice bran samples with increasing rice husk adulteration (0–100%; 2.5% increments; $n = 10$ per adulteration level).

Table 1: Principal component extraction results and variable loadings used for constructing the Rice Bran Physical Adulteration Index (RBPAI)

Parameters	Mean BD	Mean TD	Mean AR
Correlation with Mean BD	1.000	0.989	-0.970
Correlation with Mean TD	0.989	1.000	-0.971
Correlation with Mean AR	-0.970	-0.971	1.000
MSA	0.727	0.715	0.910
Communality	0.988	0.989	0.976

Table 2: Principal component extraction and loading matrix used for construction of the Rice Bran Physical Adulteration Index (RBPAI)

Statistic	Component I
Eigenvalue	2.953
Variance explained (%)	98.433
Cumulative variance (%)	98.433
Component loadings	Loading
Mean_BD	0.994
Mean_TD	0.994
Mean_AR	-0.988
Component Score	Coefficeint
BD	0.337
TD	0.337
AR	0.335

Principal component extraction produced one component with an eigenvalue greater than 1.0 (Table 2). The first principal component had an eigenvalue of 2.953 and explained 98.433% of the total variance. In contrast, the second and third components explained only 1.170% and 0.397% of the variance, respectively. The dominance of the first component indicated that a single underlying dimension could represent nearly all common variation among BD, TD, and AR. Therefore, we retained the first principal component and designated it as the Rice Bran Physical Adulteration Index.

All three variables had high absolute loadings on the retained component. Bulk density and tapped density had positive loadings of 0.994 and 0.994, respectively, whereas angle of repose had a negative loading of -0.988 (Table 2). This loading pattern indicated that higher RBPAI values were associated with higher BD and TD values and lower AR values, consistent with the physical response patterns observed

across the experimentally defined rice husk adulteration levels in Fig. 1. Based on the component score coefficients obtained from PCA, the standardized RBPAI was calculated as follows:

$$RBPAI = 0.337(Z_{BD}) + 0.337(Z_{TD}) - 0.335(Z_{AR})$$

The resulting score integrated the three correlated physical characteristics into a single quantitative index. The RBPAI scores were subsequently used as the predictor variable in the calibration model developed to estimate the proportion of rice husk in the experimentally prepared rice bran mixtures.

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3.3. Calibration of RBPAl for Predicting Rice Husk Adulteration

After developing the RBPAl, the next stage was to calibrate the index to the known husk mixing rate using experimental reference samples. This calibration aims to establish a quantitative relationship between the RBPAl value and the proportion of husks in bran, so that each index value can be translated into an estimate of the husk adulteration percentage.

The calibration curve shows a very strong linear relationship between the RBPAl value and the husk mixing rate in the reference sample (Fig. 2). The relationship is expressed by the regression equation:

$$\hat{Y} = 50.000 + 29.453(RBPAl)$$

The coefficient of determination (R^2) is 0.969, which indicates that 96.9% variation in the rate of chaff mixing can be explained by the RBPAl value (Table 3). The regression model also showed very high significance ($F = 1231.250$; $P < 0.001$), indicating that the relationship between RBPAl and husk mixing rates is very strong and consistent across the adulteration ranges used in this study.

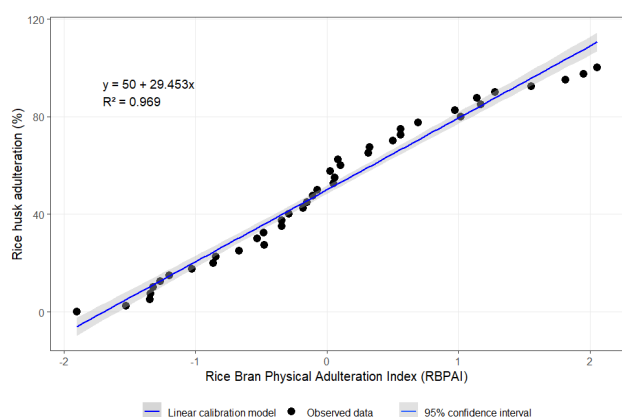


Fig. 2: Calibration curve describing the relationship between the Rice Bran Physical Adulteration Index (RBPAl) and experimentally known rice husk adulteration levels.

Table 3: Summary statistics of the linear calibration model relating the Rice Bran Physical Adulteration Index (RBPAl) to experimentally known rice husk adulteration levels

Parameters	Value
Intercept	50.000
Slope	29.453
R^2	0.969
Adjusted R^2	0.969
F	1231.250
p-value	<0.001
Standard error of estimate	5.314
MAE calibration	4.259
RMSE calibration	5.183
Raw predicted range	-6.090 to 110.663%
Standardized residual range	-1.996 to 1.881

Although the three parameters overlap across stakeholder groups, the observed variation provides a wide enough range of physical characteristics to evaluate the application of the Rice Bran Physical Adulteration Index (RBPAl) under field conditions. This diversity reflects the real state of the rice bran supply chain and underpins the assessment of RBPAl's ability to integrate multiple physical characteristics into a single composite indicator.

3.4.2. RBPAl Estimation: Based on the observed physical characteristics, we calculated the RBPAl value for each commercial bran sample using the equation developed in Phase I. The distribution of RBPAl values showed significant variation between samples and between stakeholder groups in the feed supply chain (Fig. 4). Although there is still overlap in index values between the groups, the RBPAl is able to integrate information from bulk density (BD), tapped density (TD), and angle of repose (AR) into a single quantitative measure that describes changes in the physical characteristics of bran as a whole.

Model performance shows that the calibration curve is highly accurate. The Standard Error of the Estimate (SEE) value of 5.314, the Mean Absolute Error (MAE) of 4.259, and the Root Mean Square Error (RMSE) of 5.183 indicate that the prediction error is relatively small compared to the overall adulteration range of 0–100% (Table 3). In addition, the standardized residual values were in the range of -1.996 to 1.881, which indicates the absence of extreme residuals and indicates that the model provides a good match to the reference data across the range of husk mixing levels.

The RBPAl calibration model obtained was then applied to commercial bran samples to evaluate its application as a rapid screening method under field conditions.

3.4. Application of the RBPAl to Commercial Rice Bran Samples

3.4.1. Physical Characteristics

The physical characteristics of commercial bran collected from various actors in the feed supply chain show considerable variation in the three parameters observed (Fig. 3). The values of bulk density (BD), tapped density (TD), and angle of repose (AR) showed different distributions between samples, both within and between stakeholder groups. These variations reflect the heterogeneity of the physical properties of bran in circulation in the market and indicate that the physical qualities of commercial bran are not uniform.

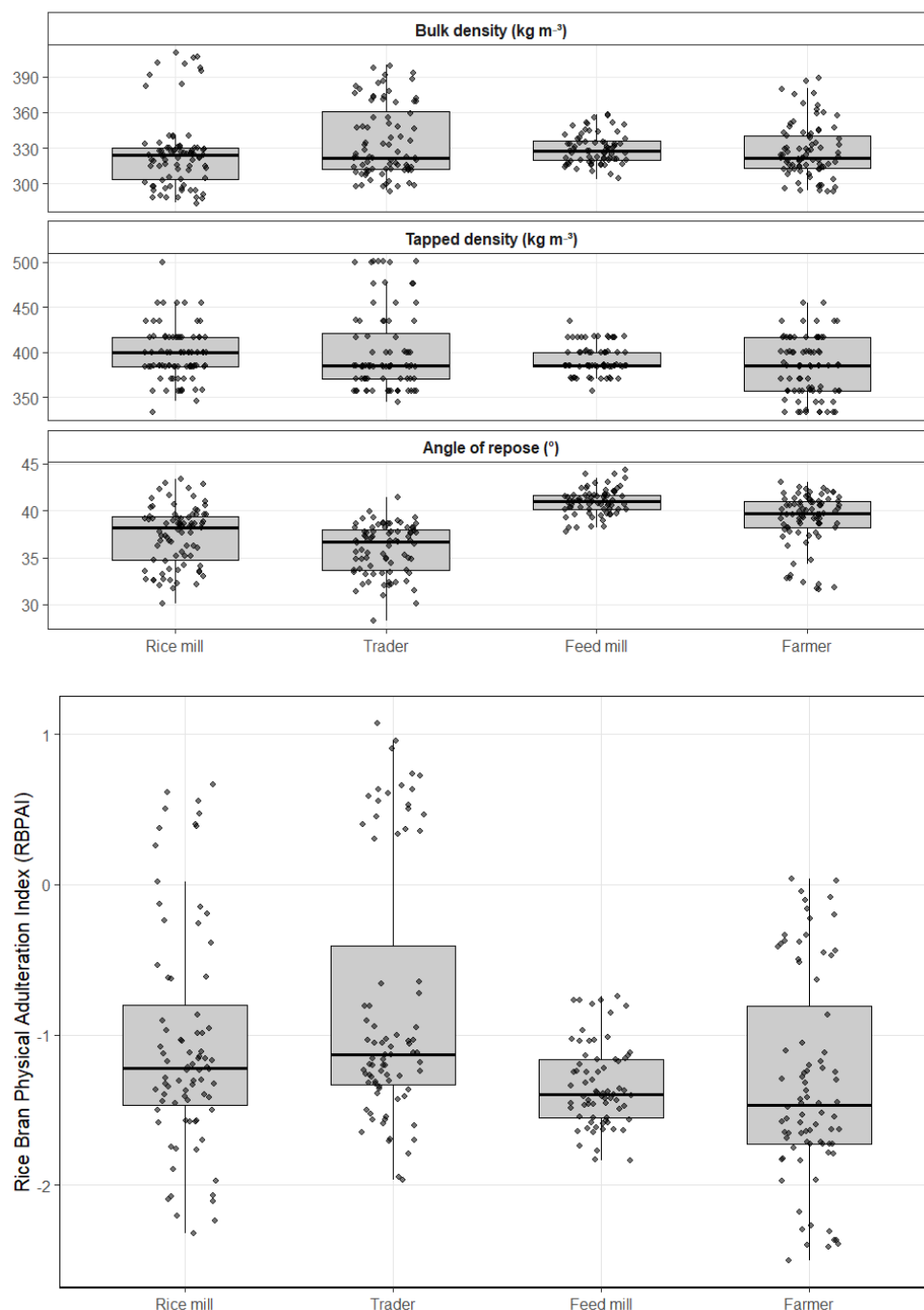


Fig. 3: Distribution of bulk density (BD), tapped density (TD), and angle of repose (AR) of commercial rice bran samples collected from different stakeholders in the poultry feed supply chain. Boxplots represent the median and interquartile range, while individual points indicate individual commercial samples

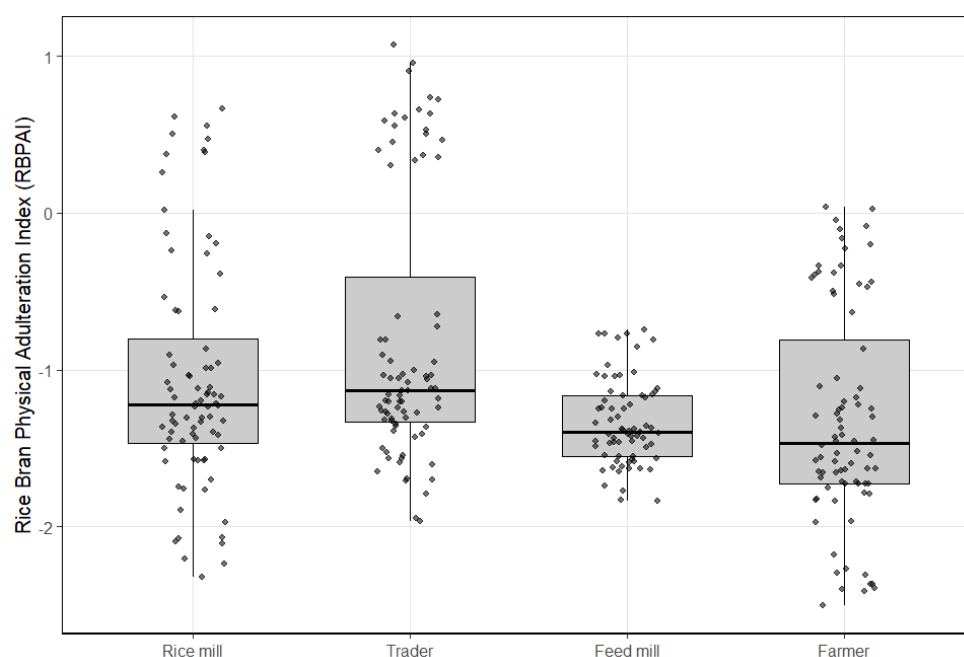


Fig. 4: Distribution of Rice Bran Physical Adulteration Index (RBPAl) values calculated for commercial rice bran samples collected from different stakeholders in the poultry feed supply chain. Boxplots represent the median and interquartile range, while individual points indicate individual commercial samples.

The RBPAl value does not directly indicate the proportion of husks in the bran, but represents the degree of change in physical characteristics produced by combining the three measurement parameters. Therefore, to interpret the index values in practice, they must be converted using the calibration model developed in Phase I. This approach allows RBPAl values obtained from commercial samples to be translated into quantitative estimates of the husk mixing rate, so the index can serve as the basis for estimating the level of adulteration under field conditions.

3.4.3. Predicted Rice Husk Adulteration: RBPAl values from commercial bran samples were then converted into estimated husk mixing rates using a calibration model developed in Phase I. Predictive results showed significant variation in husk adulteration rates in bran from different actors and locations in the feed supply chain (Fig. 5).

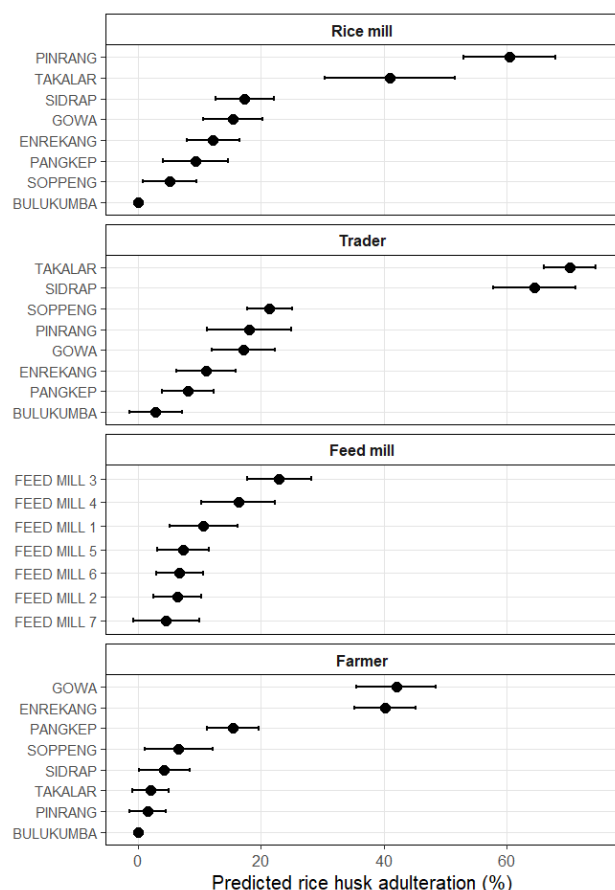


Fig. 5: Predicted rice husk adulteration levels in commercial rice bran samples collected from different stakeholders in the poultry feed supply chain. Points represent the mean predicted adulteration level for each sampling location, and horizontal error bars indicate the standard deviation.

al., 2023; Rosani et al., 2024a). Ridla et al. (2022) similarly showed that incorporating ground corn cob altered rice bran's physical characteristics. Building on this evidence, the present study combined bulk density (BD), tapped density (TD), and angle of repose (AR) into the Rice Bran Physical Adulteration Index (RBPAl). The index was calibrated using mixtures with known rice husk proportions and subsequently applied to commercial samples collected across the feed supply chain. RBPAl therefore translates several low-cost physical measurements into a single screening score. For commercial samples, however, the estimates indicate physical similarity to the experimental mixtures rather than confirmed rice husk content.

The approach used in this study rests on the premise that the incorporation of rice husk alters how the material occupies space, responds to compaction, and flows. Bulk density reflects the mass accommodated within a given bulk volume, while tapped density describes particle rearrangement and consolidation after tapping. Angle of repose reflects resistance to particle movement and pile formation. These measurements capture related yet distinct aspects of granular behavior and can be influenced by particle size, shape, surface texture, moisture, composition, and packing arrangement (Syamsu et al., 2015; Pekel, 2020; Pekel et al., 2022). Studies of feed ingredients have also shown that density and angle of repose do not always respond in parallel, because flowability emerges from several interacting particle properties rather than from density alone (Pekel, 2020). The coordinated responses observed in the present study therefore describe a systematic shift in the physical behavior of the rice bran–rice husk mixtures.

The direction of the density response deserves particular attention. In the present experiment, BD and TD increased as the proportion of rice husk increased, whereas previous studies have reported different patterns or sensitivities for bulk and compacted density. Maesaroh et al. (2023) observed lower density values following rice husk addition, while Alfaresi et al. (2023) found that compact bulk density detected differences at a lower husk inclusion level than bulk density. Rosani et al. (2024a) also showed that the physical characteristics of rice bran–rice husk mixtures varied with particle fraction and mixture composition. Differences among studies may arise from the

Overall, samples from traders show higher husk adulteration, especially in Takalar Regency (70.26%) and Sidrap (64.51%). In the *rice mill* group, the highest prediction was obtained in samples from Pinrang Regency (60.44%), while several other districts showed much lower values, including Bulukumba Regency, which was predicted not to experience adulteration. In contrast, samples from the feed mills generally showed relatively low levels of adulteration, with the highest value of 22.97% in one company, while most other companies were below 20%. At the farmer level, the prediction results show a more heterogeneous pattern, with relatively high values in Gowa and Enrekang but very low values in several other locations.

The application of RBPAl to commercial bran samples shows that the developed model is able to detect variations in the physical characteristics of bran, and provide a quantitative estimate of the husk mixing rate under field conditions. Variations in predictive results across the supply chain show that the physical quality of commercial bran is heterogeneous and indicate that RBPAl can serve as a rapid screening tool to support quality control and early identification of suspected husk adulteration in bran circulating in the market.

4. DISCUSSION

This study demonstrates that simple physical measurements can be integrated into a practical framework for screening rice husk adulteration in rice bran. Earlier studies have documented changes in nutrient composition and individual physical properties after adding rice husk or other fibrous materials (Rusyidi et al., 2023; Maesaroh et al., 2023; Alfaresi et

origin of the rice bran, degree of husk grinding, particle-size distribution, moisture content, filling procedure, and the method used to compact the sample. These contrasting responses reinforce the need to standardize preparation and measurement procedures when transferring a density-based index between laboratories or feed-supply systems.

Principal Component Analysis provided a suitable way to combine the three strongly correlated physical variables into a single composite measure. When variables describe related features of the same material, analyzing them separately can disproportionately weight information they share. PCA addresses this overlap by identifying the dominant pattern of covariation and expressing it through a smaller number of components (Jolliffe & Cadima, 2016; Cozzolino et al., 2019; Saccenti, 2024; Bian et al., 2025). In the present study, the first component accounted for 98.433% of the total variance, indicating that BD, TD, and AR were largely governed by a common underlying physical gradient. Using this component as the RBPAI retained the main pattern associated with increasing rice husk proportion while avoiding repeated interpretation of highly correlated measurements. It also provided a more practical basis for calibration, since the three measurements could be expressed as a single score before being related to the known adulteration levels.

Calibration gave the RBPAI a quantitative interpretation by relating the composite score to the known rice husk proportion in the reference mixtures. The strong linear relationship, reflected by an R^2 of 0.969, indicates that the physical gradient captured by RBPAI closely followed the experimental adulteration gradient. The relatively low MAE and RMSE show that the fitted values remained close to the known proportions used to construct the model. These statistics nevertheless represent apparent calibration performance because the same 41 adulteration levels were used for model fitting and error estimation. Reliable assessment of model transferability requires samples that are independent of the calibration data and that preserve the relevant structure and sources of variation in the target population (Westad & Marini, 2015; Lopez et al., 2023). The estimates below 0% and above 100% at the extremes arise from the unbounded nature of linear regression. Restricting operational estimates to the physically meaningful range is reasonable, although predictions near either boundary should be treated cautiously.

Application of RBPAI to commercial rice bran revealed considerable variation among stakeholder groups and sampling locations. Traders and several rice mills tended to produce higher RBPAI-derived estimates than feed mills, while samples obtained from farmers covered a wider range. Comparable heterogeneity has been reported in commercial rice bran from other regions of Indonesia. Bulk and tapped densities, crude protein, and crude fiber varied among rice mills in South Sulawesi and West Java, even when samples were grouped within the same district (Ridla et al., 2023a; Ridla et al., 2023b). Ridla et al. (2023a) also found strong relationships between density measurements and crude protein and fiber contents, indicating that variation in physical quality may reflect broader compositional differences. Market and rice-mill samples from Central Lampung likewise differed in organoleptic quality, husk content, and bulk density (Nugroho et al., 2022). The patterns observed in the present study may therefore reflect variation already present at the point of milling, followed by further changes during trading, storage, blending, and handling. They should not be interpreted as evidence that adulteration occurred at a particular stage of the supply chain.

The heterogeneity of commercial samples also highlights the distinction between controlled calibration and field application. The reference mixtures were prepared from defined materials under standardized procedures, whereas commercial rice bran may vary in rice variety, milling configuration, degree of polishing, particle-size distribution, moisture, storage history, and handling. Variety and milling intensity influence the composition of the resulting bran fraction (Kalpanadevi et al., 2018), while storage may alter moisture and physical characteristics depending on duration and packaging. Marbun et al. (2018) recorded an increase in moisture during four weeks of storage without a significant change in bulk or compact density, whereas Ridla et al. (2023a) found that longer storage and packaging conditions affected BD, TD, specific gravity, and insect infestation. These differing findings show that field variation cannot be attributed to a single factor. The present application demonstrates the feasibility of calculating RBPAI for diverse commercial samples, but it does not establish that the index is insensitive to those sources of variation.

The framework may be adapted to other feed ingredients when adding a foreign material produces reproducible changes in measurable physical properties. Ridla et al. (2022), for example, showed that ground corn cob altered the density and related physical characteristics of rice bran. Studies across broader groups of feed ingredients also confirm that flow behavior depends on the interaction of particle structure, composition, density, and compressibility (Pekel, 2020; Pekel et al., 2022). An index developed for one adulterant cannot be transferred directly to another, because the loading pattern, calibration equation, sensitivity, and useful decision range are material-specific. Adaptation would require new reference mixtures and evaluation of the physical variables that respond most consistently to the adulterant concerned.

Several limitations should guide the interpretation of the findings. The model was calibrated using experimentally prepared mixtures, while the actual rice husk content of the commercial samples was not determined independently. The field estimates should therefore be treated as model-based indications rather than absolute measurements of adulteration. Further validation should include commercial samples with known or

independently quantified rice husk contents and should represent variation in rice variety, milling system, moisture, storage, particle size, and operator. Complementary methods could provide reference measurements for this purpose. Near-infrared spectroscopy has been used to estimate the nutritional composition of commercial rice bran and to develop calibration models for adulteration assessment (Wulandari et al., 2022; Damela et al., 2024). Ultrasonic parameters have also been related to rice husk-associated lignin and crude fiber contents (Bhagaspati et al., 2021; Rosani et al., 2024b), while microscopy, color analysis, and image-based classification offer further options for confirming the presence of husk particles (Anitha et al., 2022; Albarki et al., 2023; Hernaman et al., 2024). These methods may strengthen external validation, although their additional analytical requirements should be balanced against the intended simplicity of RBPAI.

5. CONCLUSION

The physical changes associated with increasing rice husk proportion could be represented through a single composite index derived from bulk density, tapped density, and angle of repose. The first principal component explained 98.433% of the variation among these parameters and was subsequently formulated as the Rice Bran Physical Adulteration Index (RBPAI). Calibration against experimentally prepared mixtures showed a strong linear relationship between RBPAI and rice husk proportion, with an (R^2) of 0.969 and relatively low apparent calibration errors.

Application of the index to commercial rice bran revealed considerable variation in physical quality among samples collected from rice mills, traders, feed mills, and farmers. These estimates indicate RBPAI's potential as a rapid, affordable screening method for identifying samples whose physical characteristics resemble rice bran containing added rice husk. Because the actual rice husk content of the commercial samples was not independently determined, interpret the resulting estimates as preliminary indications rather than definitive measurements of adulteration. Further validation using commercial samples with known rice husk contents is needed before adopting the index for routine quality-control decisions.

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REFERENCES

- Aktar, J., Islam, S., Emon, A. I., Dey, B., & Islam, K. M. S. (2026). Feasibility of rice bran-based diet for the performance of laying hens. *Veterinary and Animal Science*, 32, 100627. <https://doi.org/10.1016/j.vas.2026.100627>
- Albarki, H. R., Agustin, A. F., Permana, A. T., & Jayanegara, A. (2023). Identification of adulterated rice bran with rice husks by using the image analytics. *IOP Conference Series: Earth and Environmental Science*, 1241(1), 012130. <https://doi.org/10.1088/1755-1315/1241/1/012130>
- Alfaresi, A. Y., Hernaman, I., & Saefulhadjar, D. (2024). Bulk density and compact bulk density of rice bran from various regencies mixed with rice husk. *Majalah Ilmiah Peternakan*, 26(3), 198–203. <https://doi.org/10.24843/MIP.2023.v26.i03.p10>
- Anitha, T., Madhuri, S. B., Alexander, G., Chandra, A. S., & Venkateswarlu, M. (2022). Foldscape based detection of rice husk and saw dust adulteration in feed ingredients and thiram contamination in cereal grains. *Journal of Animal Research*, 12(5), 647–655. <https://doi.org/10.30954/2277-940X.05.2022.6>
- Bhagaspatri, D. D., Syafei, N. S., & Hidayat, D. (2021). Investigation of husk-adulterated rice bran using ultrasonic wave. In 2021 International Conference on Artificial Intelligence and Mechatronics Systems (AIMS) (pp. 1–5). IEEE. <https://doi.org/10.1109/AIMS52415.2021.9466011>
- Bian, N., Wu, Z., Wang, J., Sun, N., Wang, Z., Zhang, G., & Zhu, L. (2025). Understanding key component factors influencing the processing performance of extruded foxtail millet. *International Journal of Biological Macromolecules*, 307(Pt. 4), 142286. <https://doi.org/10.1016/j.ijbiomac.2025.142286>
- Bodie, A. R., Micciche, A. C., Atungulu, G. G., Rothrock, M. J., Jr., & Ricke, S. C. (2019). Current trends of rice milling byproducts for agricultural applications and alternative food production systems. *Frontiers in Sustainable Food Systems*, 3, 47. <https://doi.org/10.3389/fsufs.2019.00047>
- BPS-Statistics Indonesia. (2026). Harvested area and rice production in Indonesia, 2025. Badan Pusat Statistik, Indonesia
- Cozzolino, D., Power, A., & Chapman, J. (2019). Interpreting and reporting principal component analysis in food science analysis and beyond. *Food Analytical Methods*, 12(11), 2469–2473. <https://doi.org/10.1007/s12161-019-01605-5>
- Damela, P., Despal, Adrizal, & Afnan, I. M. (2024). Detection of counterfeiting rice bran using near-infrared reflectance spectroscopy (NIRS). *IOP Conference Series: Earth and Environmental Science*, 1297(1), 012070. <https://doi.org/10.1088/1755-1315/1297/1/012070>
- Elkatry, H. O., El-Beltagi, H. S., Ahmed, A. R., Mohamed, H. I., Al-Otaibi, H. H., Ramadan, K. M. A., & Mahmoud, M. A. A. (2023). The potential use of Indian rice flour or husk in fortification of pan bread: Assessing bread's quality using sensory, physicochemical, and chemometric methods. *Frontiers in Nutrition*, 10, 1240527. <https://doi.org/10.3389/fnut.2023.1240527>
- Fidriyanto, R., Ridwan, R., Astuti, W. D., Rohmatussolihat, S., Sar, N. F., Watman, M., & Widyastuti, Y. (2020). In vitro ruminal fermentation and degradability of rice husk on rice bran substitution. *Annales Bogorieneses*, 24(1), 50–58. <https://doi.org/10.14203/ann.bogor.2020.v24.n1.50-58>
- Gul, M. Z., Das, P. P., Babu, K. R., Juarez-Colunga, S., Weber, A. M., Yoosuf, B., Alex, A. S., Srivastava, R. K., Marathi, B., Patel, S., Ryan, E. P., & Ghazi, I. A. (2026). Rice bran: A comprehensive review of phytochemicals and bioactive components with therapeutic potential and health benefits. *Nutrition Reviews*, 84(7), 1453–1472. <https://doi.org/10.1093/nutrit/nuaf147>
- Hernaman, I., Rosani, U., Dhalika, T., Tanuwiria, U. H., & Ayuningsih, B. (2024). Red-green-blue color analysis concerning rice husk incorporation in rice bran. *American Journal of Animal and Veterinary Sciences*, 19(2), 193–199. <https://doi.org/10.3844/ajavsp.2024.193.199>
- Jolliffe, I. T., & Cadima, J. (2016). Principal component analysis: A review and recent developments. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 374(2065), 20150202. <https://doi.org/10.1098/rsta.2015.0202>
- Kabir, M. H., Islam, M. N., Wazed, M. A., Ahmed, M., & Sarker, M. S. H. (2024). Optimization of milling degree for maximizing nutrient retention and yield in milled rice: A study on six common Bangladeshi rice cultivars. *Applied Food Research*, 4(2), 100587. <https://doi.org/10.1016/j.afres.2024.100587>
- Kalpanadevi, C., Singh, V., & Subramanian, R. (2018). Influence of milling on the nutritional composition of bran from different rice varieties. *Journal of Food Science and Technology*, 55(6), 2259–2269. <https://doi.org/10.1007/s13197-018-3143-9>
- Lopez, E., Etxebarria-Elezgarai, J., Amigo, J. M., & Seifert, A. (2023). The importance of choosing a proper validation strategy in predictive models: A tutorial with real examples. *Analytica Chimica Acta*, 1275, 341532. <https://doi.org/10.1016/j.aca.2023.341532>
- Maesaroh, E., Martin, R. S. H., Jayanegara, A., Aminingsih, T., & Nahrowi. (2023). Physical and chemical evaluation of rice bran with various level of husk addition. *Jurnal Ilmu Nutrisi dan Teknologi Pakan*, 21(1), 41–48. <https://doi.org/10.29244/jintp.21.1.41-48>
- Manlapig, J. J. D., & Matsui, H. (2025). Production and utilization of fermented rice bran as animal feed. *Animal Science Journal*, 96(1), e70037. <https://doi.org/10.1111/asj.70037>
- Marbun, F. G. I., Wiradimadja, R., & Hernaman, I. (2018). Pengaruh lama penyimpanan terhadap sifat fisik dedak padi. *Jurnal Ilmiah Peternakan Terpadu*, 6(3), 163–166. <https://doi.org/10.23960/jipt.v6i3.p163-166>
- Nugroho, M. D., Liman, L., Sutrisna, R., & Muhtarudin. (2022). Uji kualitas dedak padi di Kabupaten Lampung Tengah. *Jurnal Riset dan Inovasi Peternakan*, 6(3), 286–292. <https://doi.org/10.23960/jrip.2022.6.3.286-292>
- Oppong Siaw, M., McClung, A. M., Mauromoustakos, A., & Wang, Y.-J. (2023). Influence of bran layer on rice milling quality. *Cereal Chemistry*, 100(6), 1234–1249. <https://doi.org/10.1002/cche.10704>
- Pekel, A. Y., Çalik, A., Kuter, E., Alataş, M. S., Öklen, S. B., Kızıl, A., Bulat, M., & Cengiz, Ö. (2020). Impact of chemical and physical properties on flowability characteristics of corn distillers dried grains with solubles. *International Agrophysics*, 34(2), 195–202. <https://doi.org/10.31545/intagr/117502>

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- Pekel, A. Y., Kızıl, A., Çalık, A., Kuter, E., Ahsan, U., Alataş, M. S., & Kahraman, O. (2022). Classification of commonly used feed ingredients based on flow properties. *International Agrophysics*, 36(2), 123–130. <https://doi.org/10.31545/intagr/149295>
- Ridla, M., Firdayanti, Laconi, E. B., & Asikin, N. (2023b). Rice bran quality based on physical properties and chemical composition estimation in Maros Regency, South Sulawesi. *Jurnal Ilmu-Ilmu Peternakan*, 33(2), 152–161. <https://doi.org/10.21776/ub.jiip.2023.033.02.02>
- Ridla, M., Martin, R., Nahrowi, Alhasanah, N., & Fadhliah, M. (2022). Physical properties evaluation of rice bran forgery with corn cob addition. *Jurnal Ilmu Peternakan Terapan*, 6(1), 9–17. <https://doi.org/10.25047/jipt.v6i1.3203>
- Ridla, M., Sabaleku, M. R. B., & Nahrowi. (2023a). Impact of using hermetic packaging and preservative on physical properties of rice bran during storage. *Buletin Peternakan*, 47(1), 22–29. <https://doi.org/10.21059/buletinpeternak.v47i1.76880>
- Rosani, U., Hernaman, I., Hidayat, R., & Hidayat, D. (2024a). Karakterisasi dedak padi dan campuran sekam padi berdasarkan sifat fisik dan kimia. *Jurnal Agripet*, 24(1), 14–22. <https://doi.org/10.17969/agripet.v24i1.33257>
- Rosani, U., Hernaman, I., Hidayat, R., & Hidayat, D. (2024b). The relationship of lignin and crude fiber in rice bran with ultrasonic wave parameters. *Advances in Animal and Veterinary Sciences*, 12(4), 791–801. <https://doi.org/10.17582/journal.aavs/2024/12.4.791.801>
- Rusyidi, A. M., Jamila, Yamin, A. A., & Syamsu, J. A. (2023). The evaluation of nutritional quality of rice bran adulterated with rice husks as animal feed ingredients. *AIP Conference Proceedings*, 2628, 030003. <https://doi.org/10.1063/5.0144021>
- Saccenti, E. (2024). A gentle introduction to principal component analysis using tea-pots, dinosaurs, and pizza. *Teaching Statistics*, 46(1), 38–52. <https://doi.org/10.1111/test.12363>
- Syamsu, J. A., Yusuf, M., & Abdullah, A. (2015). Evaluation of physical properties of feedstuffs in supporting the development of feed mill at farmers group scale. *Journal of Advanced Agricultural Technologies*, 2(2), 147–150. <https://doi.org/10.12720/joaat.2.2.147-150>
- Westad, F., & Marini, F. (2015). Validation of chemometric models—A tutorial. *Analytica Chimica Acta*, 893, 14–24. <https://doi.org/10.1016/j.aca.2015.06.056>
- Wulandari, S., Adhyatma, M., Pantaya, D., Jayanegara, A., & Nurfitriani, R. A. (2022). Near infrared spectroscopy for the quality control of rice bran. *Livestock and Animal Research*, 20(2), 210–219. <https://doi.org/10.20961/lar.v20i2.54353>