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Path Analysis of Corn Kernel Physical Properties as Quality Indicators of Poultry Feed Ingredients

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ABSTRACT

This study aimed to identify and analyze the relationships among the physical properties of corn kernels and their impact on quality as a poultry feed ingredient using a Path Analysis approach. Five physical parameters, namely moisture content (MC), damaged kernel (DK), moldy kernel (MK), broken kernel (BK), and foreign material (FM), were evaluated in accordance with the Indonesian National Standard (SNI). Samples were taken directly from each truck that had just been received by the industry, as many as 266 trucks at different times. The sampling technique employed a stratified method based on the position of the sack in the truck, specifically the top, middle, and bottom. Each sampling point produced samples weighing approximately 100g, so the total weight of the sample per sack was approximately 300 grams. Path Analysis results revealed that moldy kernel (MK) and damaged kernel (DK) were the primary factors degrading corn kernel quality, with total effects of β=-0.510 and β=-0.402, respectively (P<0.001). MK significantly contributed to the risk of mycotoxin contamination, while DK increased susceptibility to physical and nutritional deterioration during storage. The model also uncovered significant indirect effects, where MC and BK mediated the impact of DK on quality, indicating that mechanical damage indirectly accelerates quality degradation through increased moisture retention and kernel breakage. However, the relationship between MC and MK was found to be non-significant (P=0.619), suggesting that factors such as storage temperature and ventilation have a greater influence on fungal growth than moisture content alone. Challenges related to postharvest mechanization, moisture management, and contamination control at the farm level remain critical barriers to maintaining corn quality. Therefore, improving corn quality for poultry feed applications requires an integrated strategy that includes optimizing harvest and postharvest mechanization, enhancing storage environment management, and implementing effective cleaning and sorting processes.

Keywords: Corn kernel, Physical properties, Path analysis, Poultry feed

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INTRODUCTION

Corn production in Indonesia reached 15.1 million tons, with South Sulawesi recognized as one of the main corn-producing provinces, contributing approximately 7.4% to the national total. This province yields approximately 1.13 million tons of corn from a harvested area of 191,000 hectares (BPS, 2024). The majority of corn utilization in Indonesia, approximately 75.42%, is allocated for animal feed, while the remainder is used for non-feed industries, human consumption, and seed production (DGLAHS, 2023). Corn sourced from various farming regions across South Sulawesi and utilized as poultry feed exhibits considerable heterogeneity in both physical quality and postharvest condition. This variation is strongly associated with the prevailing traditional agricultural practices employed by farmers, particularly in postharvest handling stages such as husking and shelling, drying, and storage (Syamsu et al., 2025).

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Corn kernels are the primary component in poultry feed formulation due to their high metabolic energy content, which contributes around 60% of the energy requirements and 20% of the protein requirements in chicken metabolism (Cowieson, 2005). As the primary source of carbohydrates, corn kernels play a strategic role in the feed industry, particularly in poultry rations (Klopfenstein et al., 2013; Khairani et al., 2024). However, the quality of corn kernels can show a high degree of variation, which is generally influenced by physical properties such as moisture content (MC), proportion of damaged kernels (DK), moldy kernels (MK), broken kernels (BK), and foreign material content (FM). These differences in physical characteristics have significant implications for storage stability (Coradi et al., 2020), nutritional value, and feed safety, particularly in relation to potential microbial or mycotoxin contamination (Boac et al., 2023; Zhang et al., 2024).

Feed companies in Indonesia primarily use corn as a feed ingredient, following the guidelines established by the Indonesian National Standard SNI 8926:2020 (BSN, 2020). However, corn that fully satisfies the quality specifications outlined in the SNI remains scarce, primarily due to the substantial variability in the physical properties of corn kernels (Fajar et al., 2021). Variability in the physical properties of corn kernels directly influences the final quality of poultry feed (Rodrigues et al., 2014; Koeshardianto et al., 2023). Kernels that are physically damaged or contaminated with fungi not only experience reductions in nutritional value but also pose increased risks of mycotoxin contamination, which can adversely affect animal health (Pokoo-Aikins et al., 2024). Furthermore, high moisture content can accelerate fungal and bacterial growth during storage (Karunakaran et al., 2001; Wang et al., 2020), potentially decreasing shelf life and elevating the risk of disease in poultry (Marmion et al., 2021). Thus, quantitative analysis is necessary to elucidate the relationship between the physical properties of corn kernels, thereby enhancing quality control in the livestock feed supply chain.

This study aims to analyze the relationship between the physical properties of corn kernels, specifically moisture content, damaged kernels, moldy kernels, broken kernels, and foreign material and the quality of corn kernels using the path analysis approach. The results of this study are expected to provide a scientific basis for the animal feed industry to improve corn kernel quality management throughout all stages of production, storage, and distribution.

MATERIALS & METHODS

Data Collection and Sampling Procedure

This research was conducted in Sidenreng Rappang Regency, South Sulawesi, Indonesia, in one of the corn drying industries that procure and process corn kernels for poultry feed. The research location was intentionally chosen because it is one of the centers for developing laying hens that intensively utilize corn in their feed ration formulations. Sampling was conducted on corn kernels received from farmers and suppliers by the corn drying industry, which were transported via trucks. The corn received was analyzed based on physical quality standards according to the Indonesian National Standard (SNI), including water content, percentage of damage, broken kernels, moldy kernels, and foreign matter content.

Samples were taken directly from each truck that had just been received by the industry, as many as 266 trucks at different times. The sampling technique employed a stratified method based on the position of the sack in the truck, specifically the top, middle, and bottom. Each sampling point produced samples weighing approximately 100g, so the total weight of the sample per sack was approximately 300g. This stratification technique aims to obtain a representative picture of the overall physical condition of the corn, taking into account the possibility of variations in quality between layers in the stack of sacks in the truck. Samples were collected and analyzed to evaluate the physical quality of corn kernels as a raw material for poultry feed.

Physical Quality Assessment

The parameters evaluated were moisture content (MC) and physical quality of corn kernels, namely damaged kernels (DK), moldy kernels (MK), broken kernels (BK), and foreign materials (FM).

- Moisture Content. The moisture content of corn kernel was measured using a Grain Moisture Tester model PM-650. The measurement process began by turning on the device and calibrating it by selecting the product code "corn" from the digital panel. A total of 100 grams of corn kernels was placed into the measuring chamber without compression. Once the chamber was closed and evenly pressed, the device automatically measured the moisture content based on the capacitance principle and displayed the result as a percentage (%). Each sample was measured in three replications, and the average value was used as the final moisture content data.
- Physical Quality. Physical quality assessments were conducted in accordance with the procedures specified in the Indonesian National Standard SNI 8926:2020 (BSN, 2020).
- Damaged kernels (DK). Damaged Kernels (DK). Damaged kernels are corn kernels that have been damaged due to mechanical processes, pest attacks, or signs of rot. A sample weighing 100g is taken and manually sorted to visually separate damaged kernels. Damaged kernels were weighed, and the percentage of the total sample was calculated.
- Moldy kernels (MK): Moldy kernels are seeds that exhibit visual growth of fungal mycelium, either on the surface or within the kernel, when viewed under a magnifying glass. Visual sorting was carried out on a 100g sample to separate moldy kernels. Moldy kernels were weighed, and the percentage of moldy kernels was calculated.
- Broken kernels (BK): Broken kernels are corn kernels that are not intact, where the broken kernel part is less than three-quarters of the size of a normal kernel. Measurement is performed by sorting and weighing the broken kernels from a 100g sample and then calculating the percentage.

- Foreign materials (FM). Foreign material includes all materials other than corn kernels, such as soil, gravel, plant residues, husks and other organic/inorganic materials. A 100g corn sample was weighed and then manual separation of foreign materials was carried out. The sample was weighed again, and the percentage of foreign materials was calculated.

In this study, the overall quality of corn kernels was assessed using five physical quality parameters, as previously explained, namely moisture content, damaged kernels, moldy kernels, broken kernels, and foreign materials. Each parameter was classified according to the quality threshold set by the Indonesian National Standard (SNI-8926:2020), which includes three different quality categories: Premium (P), Medium I (MI), and Medium II (MII). Corn kernels that do not meet the standards were categorized as non-category (NC). A scoring-based aggregation method was employed to derive a comprehensive quantitative score for corn kernel quality. Samples that exceed the upper limit set for the Medium II (MII) class were categorized as Non-Category (NC). Furthermore, each measured parameter was scored based on the quality range set by SNI (Table 1).

Table 1: Moisture and physical quality criteria of corn kernels for animal feed according to the Indonesian National Standard (SNI-8926:2020)

Parameters	Unit	Classes		
		Premium	Medium I	Medium II
Moisture content (MK)	%	14	14	16
Damage Kernel (DK)	%	3	5	7
Moldy Kernel (MK)	%	1	2	4
Broken Kernel (BK)	%	1	5	8
Foreign material (FM)	%	1	2	2

Samples meeting the parameter criteria for the Premium category were assigned a score of 4. At the same time, those classified within the Non-Category (NC) received a score of 1, with intermediate categories scored accordingly. To quantitatively determine the overall corn kernel quality, scores from the five parameters were aggregated using the geometric mean score.

Data Analysis

Descriptive statistical analyses were performed for the observed corn kernel physical properties. Pearson's correlation coefficient analysis, conducted using SPSS Ver. 24 (Field, 2013), was then applied to investigate linear relationships between the corn kernel's physical properties and quality. These correlation results provided the foundational evidence for developing relationship patterns utilized in subsequent path analysis (Zuffo et al., 2023).

Conceptually, these physical properties interact directly and indirectly, with some variables functioning as exogenous predictors and others acting as mediators affecting the final quality outcome. Consequently, the path analysis model incorporated both direct and indirect pathways to capture the potential biological and functional relationships among the examined variables (Santana et al., 2022).

The model was evaluated through three key procedures: construct validation, model fit assessment, and significance testing. First, validity and reliability were confirmed by assessing convergent validity (AVE>0.50), discriminant validity (Fornell-Larcker criterion) and internal consistency through Composite Reliability and Cronbach's Alpha (both>0.70) (Hair et al., 2022; Fornell & Larcker, 1981). Second, the overall goodness-of-fit was evaluated using several indices, including Chi-Square/Degrees of Freedom (DF), Comparative Fit Index (CFI), Tucker–Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA) and Standardized Root Mean Square Residual (SRMR), all of which indicated an excellent model fit. Third, the statistical significance of direct, indirect, and total effects was tested at a 95% confidence level (P<0.05), supported by bootstrapping to ensure coefficient stability (Hu & Bentler, 1999). All three assessments were generated using AMOS software (version 24.0).

Conceptual Path Model

The conceptual model for path analysis developed in this study is relationships among the physical properties of corn kernels, with kernel quality (Q) as the primary dependent variable. The pathways depicted in the model represent both direct and indirect effects of the independent variables (moisture content, damaged kernels, moldy kernels, broken kernels, and foreign materials) on the overall quality of corn kernels. A diagrammatic representation of these hypothesized variable interactions are provided in Fig. 1.

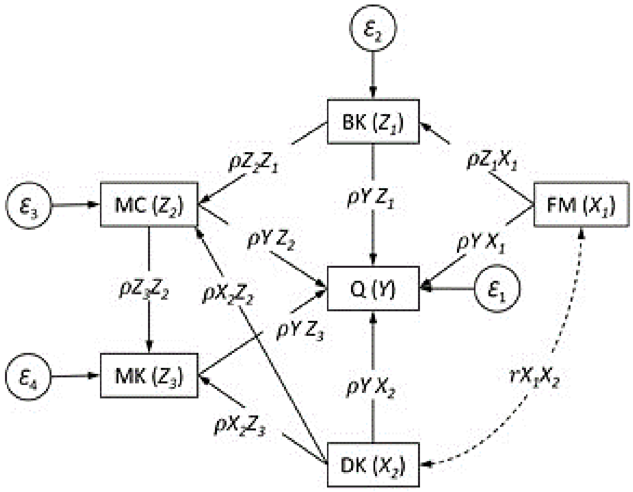

Fig. 1: Conceptual Path Analysis model illustrating hypothesized direct and indirect relationships among physical properties of corn kernels (Foreign Material [FM], Damage Kernel [DK], Broken Kernel [BK], Moisture Content [MC], and Moldy Kernel [MK]) influencing corn kernel quality (Q).

Fig. 1 presents the hypothetical path model underlying the development of the research framework, which examines factors influencing corn kernel quality. This model was developed based on the assumption that corn kernel quality is significantly influenced by various physical factors that contribute to kernel damage and fungal growth during storage and processing. Within the model, variables were categorized as follows:

- Exogenous Variables (X): Independent variables that were not influenced by other variables in the model, namely Foreign Material (FM; X_1) and Damage Kernel (DK; X_2).

- Mediating Variables (Z): Variables that mediate the effects of exogenous variables on the dependent variable, including Broken Kernel (BK; Z_1), Moisture Content (MC; Z_2), and Moldy Kernel (MK; Z_3).
- Dependent Variable (Y): The primary outcome variable was influenced by both exogenous and mediating variables, represented by Quality (Q) or corn kernel quality.

In this model, corn kernel quality (Q) serves as the main dependent variable, influenced by several physical properties: BK (Broken Kernel), MC (Moisture Content), MK (Moldy Kernel), DK (Damage Kernel), and FM (Foreign Material). Each exogenous variable contributes to quality either through direct or indirect pathways:

- Foreign Material (FM) acts as an external factor that directly influences both Broken Kernel (BK) and corn quality (Q).
- Broken Kernel (BK) directly affects corn quality, indicating that an increased proportion of broken kernels lowers the final feed material quality.
- Moisture Content (MC) affects both Moldy Kernel (MK) and Quality (Q), suggesting that higher moisture levels may increase the risk of fungal growth, ultimately leading to deteriorated kernel quality.
- Moldy Kernel (MK) directly impacts corn quality, emphasizing that the presence of moldy kernels could be a major factor in the degradation of feed material quality.

Damage Kernel (DK) also directly affects corn quality and is associated with mechanical damage factors, which are indirectly reflected in the influence of FM on BK.

RESULTS

Physical Characteristics of Corn Kernel

Descriptive statistics were used to summarize the characteristics of the data collected in this study. The descriptive statistics for each variable are presented in Table 2. As presented in Table 5, Moisture Content (MC) exhibited the highest mean value at 28.88%, with a standard deviation of 5.68%, indicating considerable variability in moisture levels across the sampled corn kernels. The mean percentages for Damage Kernel (DK) and Moldy Kernel (MK) were 2.21% and 2.03%, respectively, showing relatively lower variation. However, some samples demonstrated significantly elevated levels of physical damage and fungal contamination.

Table 2: Descriptive statistics of corn kernel physical properties and overall quality

Variables	Mean	SD	Minimum	Maximum
Moisture Content (%)	28.88	5.68	2.40	38.90
Damage Kernel (%)	2.21	1.21	0.45	8.07
Moldy Kernel (%)	2.03	1.09	0.17	5.75
Broken Kernel (%)	1.44	0.59	0.21	3.71
Foreign Material (%)	1.39	0.60	0.45	4.97
Overall quality*	2.56	0.32	1.80	3.40

*Based on geometric scores

Broken Kernel (BK) and Foreign Material (FM) recorded lower mean values of 1.44% and 1.39%, respectively, suggesting that most samples remained within acceptable industry tolerance limits. The mean overall quality score, calculated based on the geometric mean of the evaluated parameters, was 2.56, with a standard deviation of 0.32. However, considerable variation was observed, with quality scores ranging from 1.80 to 3.40. Differences likely influence the variability in corn kernel quality in moisture content, the extent of physical damage, and the degree of fungal contamination present in the samples.

Following the descriptive analysis, further statistical evaluations were conducted to explore the relationships among the physical quality parameters of corn kernels and their overall quality. Pearson's correlation analysis was performed to assess the strength and direction of linear relationships between variables, as summarized in Table 3. Additionally, multiple regression analysis was conducted to assess the direct effects of predictor variables on corn kernel quality while also checking for multicollinearity using Variance Inflation Factor (VIF) values, as presented in Table 4.

Table 3: Pearson's correlation coefficients among physical quality variables and overall corn kernel quality

Variables	Q	FM	MC	DK	BK	MK
Q	1.000					
FM	-0.536**	1.000				
MC	-0.437**	0.205**	1.000			
DK	-0.637**	0.412**	0.206**	1.000		
BK	-0.366**	0.244**	0.187**	0.170**	1.000	
MK	-0.637**	0.077ns	0.082ns	0.256**	0.063^{ns}	1.000

** P<0.01; NS=non-significant

Table 4: Direct effects of predictor variables on corn kernel quality and multicollinearity assessment

Predictors	Direct effect	Tolerance	VIF
FM	-0.145**	0.789	1.268
MC	-0.014**	0.922	1.085
DK	-0.083**	0.766	1.305
BK	-0.089**	0.917	1.091
MK	-0.146**	0.932	1.073

** P<0.01

The results of Pearson's correlation analysis (Table 3) indicate that all exogenous variables exhibited significant negative correlations (P<0.01) with corn kernel quality (Q). Among these, Damage Kernel (DK) and Moldy Kernel (MK) showed the strongest negative correlations with quality (r=-0.637), suggesting that higher levels of kernel damage and mold contamination significantly reduce corn kernel quality. Meanwhile, Foreign Material (FM) (r=-0.536), Moisture Content (MC) (r=-0.437), and Broken Kernel (BK) (r=-0.366) also demonstrated significant negative correlations with kernel quality, albeit with weaker relationships compared to DK and MK.

In addition, a significant positive correlation was observed among FM, MC, and DK, indicating that elevated moisture content in corn kernels is potentially associated with increased levels of kernel damage and foreign material contamination. Conversely, MK did not show a significant correlation with FM or BK, suggesting that other factors beyond moisture content and foreign material contamination may influence the presence of moldy kernels.

The results of the direct effect analysis through Path Analysis (Table 4) confirmed that all exogenous variables exerted significant negative effects (P<0.01) on corn kernel quality (Q). Moldy Kernel (MK) (-0.146) and Foreign Material (FM) (-0.145) demonstrated the most significant direct negative effects on quality, highlighting fungal contamination and the presence of foreign material as the primary factors that deteriorate corn quality for poultry feed applications. Damage Kernel (DK) (-0.083) and Broken Kernel (BK) (-0.089) also showed significant negative effects on quality, although with smaller contributions compared to MK and FM. Moisture Content (MC) (-0.014) exhibited the smallest direct negative effect, indicating that while moisture does influence kernel quality, its impact is relatively minor compared to other factors.

The evaluation of multicollinearity through Variance Inflation Factor (VIF) values showed that all variables had VIF values below 1.5 and Tolerance values greater than 0.7, indicating no significant multicollinearity issues within the regression model. The highest VIF values were observed for DK (1.305) and FM (1.268), but both remained well within acceptable thresholds, confirming the model's stability and validity for use in the subsequent Path Analysis.

Parameter Estimation and Relationships among Variables

Before interpreting the relationships among variables, a model fit evaluation was conducted to ensure that the Path Analysis model adequately represented the empirical data. Model fit was assessed using several indices, including Chi-Square/DF (CMIN/DF), Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR). The results of the model fit evaluation are presented in Table 5.

Table 5: Goodness-of-Fit Indices for the Path Analysis Model Evaluating Relationships among Physical Properties and Corn Kernel Quality

Fit Index	Model Value	Acceptance Threshold	Interpretation
Chi-Square/DF (CMIN/DF)	1.227	< 2.00	Goof fit
Comparative Fit Index (CFI)	0.998	> 0.90	Excellent fit
Tucker-Lewis Index (TLI)	0.994	> 0.90	Excellent fit
Root Mean Square Error of Approximation (RMSEA)	0.03	< 0.08	Good fit
Standardized Root Mean Square Residual (SRMR)	0.02	< 0.08	Good fit

CMIN/DF=Chi-Square divided by degrees of freedom; CFI=Comparative Fit Index; TLI=Tucker-Lewis Index; RMSEA=Root Mean Square Error of Approximation; SRMR=Standardized Root Mean Square Residual. Values within the accepted thresholds indicate that the model has a good fit with the empirical data.

The results indicate that the model exhibits a perfect fit with the empirical data, as evidenced by CFI and TLI values exceeding 0.90, along with RMSEA and SRMR values below 0.08, demonstrating minimal estimation error. Therefore, the Path Analysis model is deemed suitable for analyzing the relationships among the physical properties of corn kernels and their quality. Following the confirmation of model fit, the relationships among variables were analyzed based on the standardized path coefficients, as presented in Fig. 2. The Path Analysis includes the estimation of direct, indirect, and total effects, with detailed results summarized in Table 6.

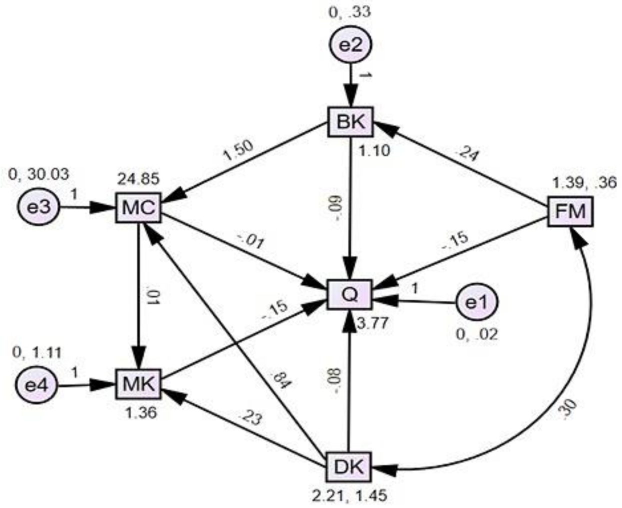

Fig. 2: Standardized Path Coefficients in the Path Analysis Model Evaluating Relationships among Physical Properties and Corn Kernel Quality.

Table 6: Path Coefficient Estimates, Standard Errors (SE), Critical Ratios (CR), and Significance Levels in the Path Analysis Model

Relationship	Standardized Estimate (β)	SE	CR	P-value
BK <--- FM	0.244	0.06	3.977	***
MC <--- BK	1.501	0.59	2.545	0.011
MC <--- DK	0.844	0.29	2.909	0.004
MK <--- DK	0.226	0.056	3.995	***
MK <--- MC	0.006	0.012	0.497	0.619
Q <--- DK	-0.083	0.008	-10.819	***
Q <--- MK	-0.146	0.008	-19.089	***
Q <--- MC	-0.014	0.001	-9.183	***
Q <--- BK	-0.089	0.014	-6.271	***
Q <--- FM	-0.145	0.015	-9.629	***

P<0.001 indicates a highly significant relationship.

The path diagram (Fig. 2) reveals the following key findings:

- Foreign Material (FM) has a significant direct adverse effect on both Broken Kernel (BK) (standardized coefficient=0.24) and Corn Kernel Quality (Q) (-0.15). This suggests that an increase in foreign material content worsens physical integrity (broken kernels) and directly reduces kernel quality.
- Broken Kernel (BK) negatively influences Quality (Q) (coefficient=-0.10), confirming that physical damage to kernels diminishes their overall quality.
- Moisture Content (MC) shows a significant positive effect on Moldy Kernel (MK) (coefficient=0.08), although the relationship is relatively weak. However, MC has a negative effect on Q (coefficient = -0.01).
- Moldy Kernel (MK) exerts a strong direct adverse effect on Quality (Q) (coefficient=-0.15), indicating that fungal contamination significantly deteriorates corn quality.
- Damage Kernel (DK) has a direct adverse effect on Quality (Q) (coefficient=-0.08) and a positive effect on Moisture Content (MC) (coefficient=0.21). This suggests that higher kernel damage may promote increased moisture retention, indirectly raising the risk of fungal growth.

In addition to these direct effects, the model demonstrates that FM influences Q indirectly through its effect on BK, and DK affects Q indirectly via MC and MK, showing a chain effect where kernel damage elevates moisture content, which in turn promotes mold growth and further quality degradation. The residual variances (e_1, e_2, e_3, e_4) in the model account for unexplained variability in Q, BK, MC, and MK, suggesting that other unmeasured factors may also contribute to variations in these properties.

Path Coefficient Estimation Results

The path analysis results revealed that several variables exert significant direct effects on corn kernel quality (Q). Broken Kernel (BK), Moisture Content (MC), Moldy Kernel (MK), and Damage Kernel (DK) showed significant negative relationships with kernel quality, indicating that higher values of these factors lead to a decline in overall corn quality. Additionally, Foreign Material (FM) had a significant adverse direct effect on Q, suggesting that contamination with foreign matter can substantially reduce corn kernel quality.

Several variables indirectly influenced corn kernel quality. Specifically, Damage Kernel (DK) affected Q through Moisture Content (MC) and Moldy Kernel (MK). This pathway suggests that damaged kernels are more likely to retain a higher moisture content, which subsequently promotes fungal growth and compromises quality. Broken Kernel (BK) served as a mediator between Foreign Material (FM) and kernel quality (Q), suggesting that mechanical damage and contamination contribute to increased kernel breakage, ultimately leading to quality deterioration. The estimated indirect effects are presented in Table 7. The total effects in the model represent the combined direct and indirect effects. Table 8 summarizes the total effects of each variable on corn kernel quality (Q).

Table 7: Indirect Effects of Physical Properties on Corn Kernel Quality in the Path Analysis Model

Relationship	Standardized Estimate (β)	P-value
Q <--- DK (via MC, MK)	-0.319	***
Q <--- BK (via MC, MK)	-0.245	***
Q <--- FM (via BK)	-0.28	***

*P<0.001 indicates highly significant effects.

Table 8: Total Effects (Direct and Indirect) of Physical Properties on Corn Kernel Quality in the Path Analysis Model

Relationship	Standardized Estimate (β)	P-value
Q <--- DK	-0.402	***
Q <--- MK	-0.510	***
Q <--- MC	-0.245	***
Q <--- BK	-0.169	***
Q <--- FM	-0.280	***

*P<0.001 indicates highly significant effects.

The results show that Moldy Kernel (MK) had the most significant total negative effect (-0.510) on corn kernel quality, confirming that fungal contamination is the most influential factor in degrading kernel quality. Based on the model validation results, the developed model demonstrates an excellent fit with the empirical data. The Goodness-of-Fit (GoF) evaluation indicated that SRMR (0.020) and RMSEA (0.030) values were well below the 0.08 threshold, reflecting minimal differences between the observed and predicted covariance matrices. Additionally, high CFI (0.998) and TLI (0.994) values, both above 0,90 confirm that the model performed considerably better than the baseline model. The Chi-square/DF ratio (1.227) further suggests that the model achieved simplification without sacrificing explanatory power. Overall, these results confirm that the model meets all necessary GoF criteria and is reliable for further analysis.

The path analysis results indicate that Moldy Kernel (MK) had the most significant total negative impact on corn kernel quality (β=-0.510, P<0.001). This finding highlights that fungal contamination is the primary factor contributing to the deterioration of corn used in poultry feed. This finding is consistent with previous studies, which indicate that mold not only reduces the nutritional content of corn kernels but also increases the risk of mycotoxin contamination, potentially negatively affecting livestock health. Additionally, the Damage Kernel (DK) also exhibited a significant negative effect on corn quality (β=-0.402, P<0.001), indicating that mechanically damaged kernels are more susceptible to oxidation and microbial growth during storage.

Both Foreign Material (FM) and Moisture Content (MC) were found to have negative effects on corn quality, although their impacts were less pronounced compared to MK and DK. Contamination by foreign material can reduce feed processing efficiency and elevate contamination risks. At the same time, high moisture levels can accelerate kernel degradation, affecting the storage stability and shelf life of feed materials. Therefore, effective moisture management and postharvest cleaning processes are crucial for maintaining corn quality in the feed industry.

Broken Kernel (BK) had both direct and indirect negative effects on corn quality, although its overall impact was smaller (β=-0.169, P<0.001) compared to DK and MK. While broken kernels increase vulnerability to contamination, their overall impact on quality was not as severe as that of fungal contamination or mechanical damage. Nevertheless, BK can serve as an indicator of poor postharvest handling and mechanization practices, which must be addressed in quality control strategies.

Regarding the indirect pathways, the study found that Moisture Content (MC) did not have a significant effect on Moldy Kernel (MK) (β=0.006, P=0.619). This suggests that moisture alone may not be the dominant factor influencing fungal growth under the observed conditions. Other environmental factors, such as temperature and storage conditions, which were not included in the model, could play a more critical role. Consequently, the MC → MK pathway may need to be revised in future model developments by incorporating broader environmental variables.

DISCUSSION

The results of this study demonstrate that Damage Kernel (DK) and Moldy Kernel (MK) are the primary factors degrading corn kernel quality, as evidenced by their total effects of β=-0.402 and β=-0.510, respectively (P<0.001). Mechanical damage occurring during harvesting, postharvest handling, and transportation not only deteriorates the physical and visual quality of corn kernels but also increases the risk of secondary contamination, such as microbial infestation and nutrient degradation due to ruptured kernel structures. Damaged kernels are more vulnerable to oxidation, insect attack, and microbial colonization during storage. Blazer et al. (2023) emphasized that a high proportion of damaged corn kernels adversely affects feed quality and nutrient content, which must be carefully addressed in quality control and feed formulation strategies. As demonstrated by Boac et al. (2023), handling stresses can lead to increased kernel breakage. Kruszelnicka et al. (2024) suggest that the weakening and breakage behavior of corn kernels under repeated mechanical stress is significantly influenced by their moisture content and physical dimensions, highlighting the susceptibility of damaged kernels to further quality degradation during storage and handling. Bulk flow behavior and handling stresses are known to influence kernel stability, with physical properties such as friction and bulk density playing crucial roles in the mechanical damage and quality deterioration of shelled corn.

Moldy Kernel (MK) had a profoundly negative impact on corn quality, not only reducing feed industry acceptance but also posing significant risks to food safety. Moldy kernels can produce harmful mycotoxins, such as aflatoxins and fumonisins, which have toxic effects on both animal and human health (Bryden, 2012). In the context of global trade, the presence of moldy kernels poses a significant challenge to supply chains (Zhang et al., 2024), as many importing countries impose strict limits on mycotoxins in feed materials. Thus, mold contamination affects not only the quality but also the food safety compliance and international competitiveness of corn products.

Beyond direct effects, the developed Path Analysis model also revealed important indirect effects through mediating variables. Moisture Content (MC) and Broken Kernel (BK) act as mediators linking Damage Kernel (DK) to corn quality (Q), indicating that DK reduces quality both directly and indirectly by increasing moisture levels and kernel breakage, both of which accelerate quality deterioration during storage. Nalle et al. (2022) stated that the moisture level affects the percentage of damaged and moldy kernels.

For instance, the pathway DK → MC → Q suggests that mechanically damaged kernels tend to retain higher moisture levels, which negatively affects their final quality. However, the relationship between MC and MK was not significant ($\beta=0.006$, $P=0.619$), suggesting that moisture alone does not drive mold growth. Other factors, such as storage temperature, ventilation, and the initial fungal inoculum level, may play a more significant role. Although moisture content alone was not significantly correlated with mold development in this study, previous research by Zheng et al. (2024) has demonstrated that moisture remains a critical factor influencing corn kernel stability and compositional quality, particularly in multi-environmental conditions. Therefore, moisture management strategies must be combined with control of the storage environment to prevent mold development and maintain corn quality effectively.

Another indirect pathway, FM → BK → Q, shows that Foreign Material (FM) contamination contributes to increased broken kernels, subsequently reducing corn quality. Foreign materials, such as soil residues, plant debris, and other particulates, may exacerbate mechanical abrasion during storage and handling, resulting in greater kernel damage. Moreover, foreign material can act as a carrier for pathogens, including fungi and bacteria, accelerating quality deterioration. Therefore, minimizing foreign material contamination is crucial not only for hygiene but also for reducing mechanical damage and preserving overall corn quality.

The Path Analysis model highlights how corn's physical properties interact to determine final quality. Indirect effects reveal that several variables influence quality not only independently but also through mediated relationships. Thus, improving corn kernel quality remains challenging at the farm level, particularly in areas such as harvest and postharvest mechanization, moisture management, and contamination control during storage.

Corn batches are procured from smallholder farmers across multiple regions both within and beyond South Sulawesi Province, resulting in considerable variability in conditions and quality. In general, farmers rely on traditional farming practices, particularly in postharvest processes such as shelling, drying, and storage (Cecil et al., 2023). Suboptimal mechanization often results in increased damaged and broken kernels, which subsequently degrade quality (Bendinelli et al., 2020). Moreover, many farmers still rely on uncontrolled natural drying methods (Arslan & Alibaş, 2024), resulting in inconsistent moisture levels that increase the risk of mold growth, particularly under poor storage ventilation and high humidity conditions (Dagnas & Membré, 2013). Contamination with foreign materials remains a common issue at the farm level due to uneven sorting and cleaning processes (Hagen et al., 2020). Limited access to improved postharvest technology contributes to higher levels of soil residue, stalk fragments, and other particulates mixed with corn (Mutungi et al., 2022). Foreign materials not only directly lower quality but also serve as carriers of pathogens, expediting deterioration during storage. This finding supports the concept that grain storage must be viewed as a complex ecosystem where physical and biological factors interact dynamically, and moisture content alone does not entirely predict fungal growth risks (Dunkel, 1992). Thus, the main challenges in the corn production and storage system at the farm level are related to the limited availability of postharvest technology and infrastructure, both of which affect the efficiency of quality control within the poultry feed supply chain.

Efforts to improve corn kernel quality must adopt a holistic approach, considering the interactions among variables across production and storage systems. Based on these findings, several key implications for quality control in the poultry feed industry can be drawn: 1) Reducing Damage Kernel (DK) and Broken Kernel (BK) levels through improved harvest and postharvest mechanization, as both have direct and indirect effects on quality deterioration; 2) Controlling Moisture Content (MC) within optimal limits, but with a comprehensive strategy that considers environmental storage factors; 3) Minimizing Foreign Material (FM) contamination, as it contributes to increased kernel breakage and accelerates quality decline during storage and distribution; and 4) Preventing Mold Growth by managing storage environments effectively, including temperature control, proper ventilation, and monitoring for fungal presence during postharvest stages.

Conclusion

This study identified and analyzed the relationships among the physical properties of corn kernels and their effects on quality as a poultry feed ingredient using a Path Analysis approach. The findings revealed that Moldy Kernel (MK) and Damage Kernel (DK) were the primary factors reducing corn kernel quality, with total effects of β=-0.510 and β=-0.402, respectively (P<0.001). The presence of moldy kernels significantly contributes to the risk of mycotoxin contamination, while damaged kernels increase vulnerability to quality degradation during storage.

In addition to direct effects, the study also demonstrated important indirect effects through mediating variables. Moisture Content (MC) and Broken Kernel (BK) acted as mediators in the pathway linking DK to corn quality. This finding confirms that mechanical damage not only has a direct negative impact on quality but also indirectly accelerates quality deterioration by increasing moisture levels and kernel breakage during storage. However, the relationship between Moisture Content (MC) and Moldy Kernel (MK) was found to be non-significant (P=0.619), suggesting that other factors, such as storage temperature and ventilation, play a more decisive role in mold development than moisture content alone.

Challenges in postharvest mechanization, moisture management, and the removal of foreign material persist at the farm level, hindering effective control of corn quality. Uncontrolled drying processes and suboptimal storage infrastructure contribute to elevated risks of contamination and quality deterioration. Therefore, improving corn kernel quality within the poultry feed supply chain requires a more integrated approach, including optimizing mechanization, effectively managing the storage environment, and enhancing the efficiency of cleaning and sorting processes.

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Author's Contribution: SP conducted the research design, developed the methodology, collected and analyzed the data, and prepared the manuscript. JAS contributed to data collection, data validation, and critical review of the manuscript. Both authors reviewed and approved the final version of the manuscript.

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