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Research Article

Assessment of Pineapple Agro-Industrial Waste in the Production of Extruded Feed for Beef Cattle

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Abstract | The valorization of agro-industrial waste through extrusion technologies represents a promising strategy for the development of sustainable compound feeds for beef cattle. This study evaluated the effect of temperature (120–150 °C) and moisture content (16–22 g/100 g) on the extrusion process of a diet formulated with agro-industrial pineapple residues (*Ananas comosus*), corn, soybean, molasses, and a mineral mixture. A central composite design was employed to assess the physicochemical and nutritional behavior of the resulting extrudates. The results revealed that increasing moisture content significantly reduced torque, specific mechanical energy, and expansion index, while increasing bulk density and maximum compression breaking force, thereby enhancing the structural strength of the product. Temperature positively influenced starch gelatinization and water absorption capacity, although it was associated with a decrease in protein and fat content. Additionally, an increase in crude fiber was observed under higher thermal conditions. These findings demonstrate that pineapple residues can be effectively incorporated into extruded feed formulations, optimizing functional, physical, and nutritional properties relevant to intensive beef production systems. This research contributes to the sustainable utilization of agricultural by-products and the design of more efficient and resilient formulation strategies in the animal feed industry.

Keywords | Agro-industrial waste, Beef cattle, Compound feed, Extrusion, Pineapple, Sustainability

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INTRODUCTION

The growing demand for beef cattle feed has driven the search for alternative sources that are both sustainable and economically viable, capable of partially replacing conventional ingredients and thereby reducing the pressure on traditional agricultural resources. In this context, agro-industrial residues represent a promising option due to their wide availability, low cost, and suitable nutritional profile (Rivera-Mirón *et al.*, 2020). In particular, by-products derived from pineapple processing, such as peels and residual pulp, contain significant amounts of dietary fiber and nutrients that can be utilized in the formulation of balanced diets for ruminants (Vivar-Vera *et al*., 2023). Several studies have explored the incorporation of agro-industrial by-products into beef cattle diets. Rahmawati *et al*. (2022) reported that diets formulated with agro-industrial waste, including fruit processing by-products, can enhance both productivity and digestibility in cattle, highlighting their economic and environmental potential. Similarly, de Paula and de Faria Júnior (2018) reviewed the use of pineapple by-products in ruminant diets, emphasizing their capacity to reduce feed costs and minimize agro-industrial waste volumes. Idayanti *et al*. (2022) also documented that the inclusion of pineapple residues as a forage source can significantly contribute to the sustainability of bovine production systems. Among the most versatile technologies for the development of compound feeds is extrusion. This process is widely employed to improve the nutritional, functional, and physical properties of feedstuffs, as it facilitates digestibility and handling (Juárez-Barrientos *et al*., 2025; Téllez-Morales *et al*., 2025a). Extrusion involves subjecting ingredient blends to controlled conditions of temperature, moisture, and mechanical shear, thereby producing products with enhanced physicochemical and nutritional characteristics (Téllez-Morales *et al*., 2025b). However, the effective integration of pineapple residues into such processes requires specific research to evaluate their behavior during extrusion and their impact on the final product properties. Therefore, the objective of the present study was to evaluate the effect of moisture content and temperature during the extrusion process on the physicochemical and nutritional properties of compound feeds formulated with agro-industrial pineapple residues, to determine the optimal conditions for producing feeds suitable for intensive beef cattle feeding systems.

MATERIALS AND METHODS

Materials

Agro-industrial waste (peel and pulp) of pineapple (*Ananas comosus*) was donated by the Santa Monica Products Plant, S.A. de C. V., Loma Bonita, Oaxaca, Mexico. White corn grains (*Zea mays* L.) were obtained from a local market in San Juan Bautista Tuxtepec, Oaxaca, Mexico. Soybean flour (Food Technologies Trading S.A. de C.V., Mexico). Cane molasses (Mine-Gan, Química Industrial Agropecuaria S.A. de C.V., Mexico), mineral mixture (Cal-1000, Laboratorios Nutrifarma S.A.S. Colombia [Calcium 30% (minimum), Magnesium 1.30%, Zinc 0.50%, Copper 0.20%, Cobalt 0.02%, moisture 5%, excipient q.s.p. 100 g.]).

Conditioning and characterization of raw materials

The agro-industrial waste pineapple residues were washed and cut into 2 x 2 cm cubes and dried at 60 °C for 24 h. Dried samples were ground and sieved (mesh No. 35 = 0.595 mm) (Rivera-Mirón *et al*., 2020). The corn kernels were ground and sieved (mesh No. 35 = 0.595 mm). The proximate chemical composition of the raw materials and the extruded products obtained was determined according to AOAC Standard Methods (2019): moisture, ash, protein, fat, fiber, and nitrogen-free extract were determined by difference.

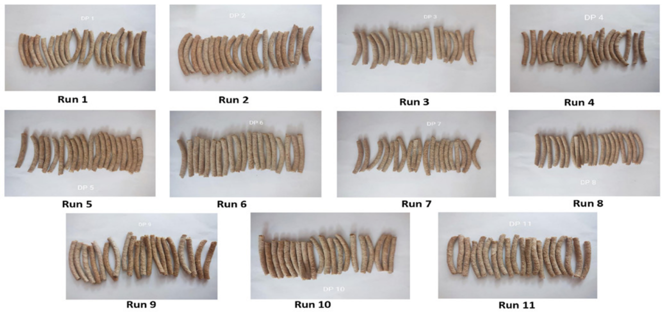

Figure 1: Photographs of the extruded products obtained.

Experimental diet formulation

The diet was established using the nutritional content of cattle (Reyes-Jáquez *et al*., 2011; Delgado *et al*., 2020) as a reference. The balanced diet was prepared with a powder of agro-industrial pineapple waste (Table 1). Before the extrusion process, the formulation was mixed manually to obtain a uniform moisture distribution according to the experimental design (Table 2).

Table 1: Diet formulation (g/100 g).

Ingredients	Proportion
Corn flour	50
Pineapple agro-industrial residues flour	25
Soybean flour	10
Mineral mix	10
Molasses	5

Table 2: Factors and variation levels of experimental design.

Factor	Levels of variation				
	-α	-1	0	+1	+α
X_1 = Moisture content (g/100 g)	14.76	16.00	19.00	22.00	23.24
X_2= Temperature (°C)	113.79	120.00	135.00	150.00	156.21

α = 1.1414

Extrusion process

Extrusion was carried out using a single-screw extruder (Model E19/25 D, Brabender Instruments Inc., South Hackensack, N.J., U.S.A.) in a laboratory, with the following temperature profile: Zone 1 = 90 °C, zone 2 = 100 °C, zone 3 = 110 °C and zone 4 = 120 - 150 °C (according to the experimental design); feed rate 200 g/min; screw speed 200 rpm; screw compression force 1:1 and internal diameter of the circular output die of 5 mm. Before extrusion, the formulations were mixed, and the moisture content was adjusted according to the experimental design (Table 2). The extruded products were dried at 50 °C for 2 h, then stored in refrigeration (4-6 ºC) in sealed polyethylene bags for later analysis.

Determination of torque

Torque was obtained directly from the extruder control panel. Average values of triplicate readings were recorded for each treatment.

Determination of specific mechanical energy (SME)

SME was determined according to the procedure described by Pensamiento-Niño *et al.* (2018) reported in J/g, using the following equation:

$$SME = \frac{\Omega \times \omega \times 60}{M_{feed}} \quad \dots (1)$$

Where; Ω is the torque exerted on the extruder impeller (N-m), ω is the angular velocity of the screw (rad/sec) and M_{feed} is the mass flow of the feed (g/min).

Expansion index (IE) and bulk density (BD)

The expansion index was determined by dividing the diameter of the extrudate by the diameter of the extruder exit hole. The bulk density is determined by dividing the weight of the sample by the volume of the extruded product (Navarro-Cortez *et al.*, 2016).

Maximum compression breaking force (MCBF)

The maximum compression breaking force was determined using a TA-XT2 texture analyzer (Texture Technologies Corp. Scarsdale NY/Stable Micro Systems, Haslemere, Surrey, UK) in compression mode, using a Warner-Bratzler cutting blade with a test speed of 5 mm/s. Fifteen repetitions were performed per treatment, and the average values were reported in Newton (N).

Water absorption index (WAI) and water solubility index (WSI)

The WAI and WSI were determined in triplicate using the process described by Rodríguez-Miranda *et al.* (2014).

pH and color

Measured in 1 g of sample diluted in 10 mL of distilled water (Navarro-Cortez *et al.*, 2016). Lightness (*L**), *a** (positive values for red tones and negative values for green tones), *b** (positive values for yellow tones and negative values for blue tones) determined in a Hunter Lab colorimeter (MiniScan Hunter Lab, model 45/0L, Hunter Associates Lab., Ind., Reston, Virginia U.S.A).

Design of experiments and statistical analysis

A composite central design with two independent variables (temperature 120-150 °C and moisture content 16 - 22%) was used using commercial software (Design-Expert 8.0.2, Statease Inc., Minneapolis, MN, USA). Results were analyzed for multiple linear regression and analysis of variance (ANOVA). Using commercial software, the experimental data were fitted to a second-order quadratic model, and regression terms were examined by ANOVA for each response.

RESULTS AND DISCUSSION

Chemical composition of raw materials

Molasses exhibited the highest content of nitrogen-free extract (NFE), followed by corn flour, agro-industrial pineapple residues, and soybean flour (Table 3). This hierarchy highlights the potential of these ingredients in the formulation of balanced diets for ruminants, as molasses is rich in fermentable sugars, making it an excellent energy source for cattle (Pélagie *et al.*, 2022). Corn flour, on the other hand, is characterized by its high carbohydrate content, primarily starch (Rodríguez-Miranda *et al.*, 2011). The elevated NFE levels in molasses and corn suggest their suitability for energy-rich diets, particularly for lactating cows and growing calves (Salvador-Loreto *et al.*, 2016).

Table 3: Proximal chemical composition (g/100 g) of raw materials (dry basis).

Raw material	Ash	Protein	Fat	Fiber	NFE
Corn flour	1.44± 0.03	8.77± 0.53	3.98± 0.37	1.62± 0.006	84.19± 0.06
Pineapple agro-industrial residues flour	5.82± 0.03	13.24± 0.38	2.25± 57	12.57± 0.53	66.13± 0.01
Soybean meal flour	6.92± 0.05	28.69± 0.97	3.64± 0.36	3.25± 0.88	57.51± 0.03
Molasses	7.20± 0.12	5.80± 0.45	0.10± 0.04	0.50± 0.08	86.9 0± 0.96

The values presented are the average ± standard deviation of three determinations. NFE= Nitrogen free extract.

The high lipid content observed in both corn and soybean flours (Table 3) supports their use in the development of high-energy-density feed products. Conversely, pineapple residues represent a strategic alternative for reducing agro-industrial waste and enhancing the sustainability of food systems (Strange and Schaich, 2000).

The high fiber content in pineapple residues is primarily attributed to their cellulose fraction, which constitutes a relevant source of energy for ruminants (Pélagie *et al.*, 2022). This characteristic aligns with the growing trend of utilizing agro-industrial by-products as tools to improve feed efficiency and promote sustainability in livestock production systems.

Although corn flour and molasses contain less fiber compared to pineapple residues, they contribute energy and improve feed palatability (Kasymbek *et al*., 2023). These ingredients are commonly used as supplements in fiber-rich diets, supporting a more balanced formulation (Kasymbek *et al*., 2023). The inclusion of agro-industrial by-products, such as pineapple residues, not only enhances nutrient conversion but also reduces the environmental impact associated with livestock production (Anisimova *et al*., 2023).

The utilization of agro-industrial by-products in animal nutrition contributes to both environmental sustainability and economic efficiency in production systems (Anisimova *et al*., 2023; Rahmawati *et al*., 2022). Among the ingredients evaluated, soybean flour showed the highest protein content, followed by pineapple residues, corn flour, and molasses (Table 3). This composition underscores the nutritional value of various agricultural by-products in cattle diets. The high total nitrogen content in soybean flour makes it a high-quality protein source for the formulation of compound feeds (Pélagie *et al*., 2022). Several studies have indicated that plant-based by-products, including pineapple residues, exhibit superior digestibility compared to conventional ingredients such as corn silage (Idayanti *et al*., 2022). This suggests that, beyond protein content, ingredient digestibility is a critical factor in designing ruminant diets. The inclusion of multiple by-products can improve feed efficiency and reduce costs without compromising animal performance, as demonstrated by formulations incorporating pineapple residues (de Paula and de Faria Júnior, 2018). Regarding ash content, molasses recorded the highest value, followed by soybean flour, pineapple residues, and corn flour (Table 3). The high mineral concentration in molasses reinforces its role as a micronutrient source in cattle diets, a fact widely documented in the scientific literature.

Torque and SME

The regression analysis results (Table 4) indicate that the linear effect of moisture content in the feed mixture was the key factor that significantly ($p < 0.05$) influenced both torque and SME during the extrusion process. In contrast, quadratic effects, the interaction between temperature and moisture, and the linear effect of temperature did not exhibit statistically significant influences on these variables. The coefficient of determination (R^2) obtained was 0.73 for both torque and SME, indicating a good fit of the predictive model.

Table 4: Regression coefficients of the response surface models.

Responses	Coefficients						
	Interception	Lineal		Quadratics		Interaction	
	b_0	X_1	X_2	X_1^2	X_2^2	X_1X_2	R^2
Torque	20.55	-4.95	-2.55	1.75	0.76	2.30	0.73
SME	171.12	-37.69	-21.20	12.26	3.28	17.07	0.73
EI	1.11	-0.01	0.00	-0.01	-0.01	0.00	0.75
BD	1.07	-0.01	-0.03	0.00	0.00	-0.04	0.64
MSBF	59.35	3.25	-0.10	-0.32	4.94	-11.10	0.78
WAI	3.80	-0.02	0.12	0.05	-0.16	0.07	0.79
WSI	13.87	0.02	-0.29	-0.21	-0.75	-0.67	0.89
pH	5.58	0.00	0.03	-0.03	0.00	-0.03	0.72
L*	67.77	0.34	-2.85	1.68	1.18	-0.04	0.92
a*	4.56	0.08	0.45	-0.06	0.03	0.16	0.95
b*	18.70	0.38	-0.16	0.04	-0.09	0.32	0.69
Moisture	8.35	0.58	0.00	0.51	0.08	0.11	0.55
Ash	15.66	-0.05	-0.38	-0.34	-0.07	0.16	0.79
Fat	15.66	-0.05	-0.38	-0.34	-0.07	0.16	0.61
Protein	8.28	0.31	-1.14	-0.20	-0.85	1.52	0.87
Fiber	8.18	0.50	0.80	0.37	0.85	0.68	0.85
NFE	57.70	-1.22	0.81	-0.46	0.02	-2.92	0.90

*Bold parameters are significant ($p < 0.05$). X_1 = Moisture content; X_2 = Temperature. SME = Specific mechanical energy; EI= Expansion index; BD = Bulk density; MSBF = Maximum shear breaking force; WAI= Water absorption index; WSI= Water solubility index, NFE = Nitrogen free extract.

The response surface plots (Figures 2a, c) and contour plots (Figures 2b, d) show that increasing both temperature and moisture content led to a decrease in torque and SME values, respectively. Under conditions of low temperature (110–135 °C) and low moisture content (14–17 g/100 g), the highest torque (42–45 N) and SME (420–340 J/g) values were recorded. Notably, within the temperature range evaluated, temperature did not exert a statistically significant effect ($p > 0.05$) on these responses. The negative effect of moisture content on torque and SME can be attributed to the fact that higher moisture levels reduce the processing difficulty of the mixtures by modifying their rheological properties and texture (Meng *et al*., 2023). Elevated moisture content is commonly associated with lower melt viscosity, which in turn decreases the torque and energy required for extrusion. Sun *et al*. (2023) reported that increased moisture in the formulation reduces the viscosity of molten proteins, resulting in lower torque demands during extrusion. Complementarily, Singh *et al*. (2024) noted that higher feed moisture content significantly reduces SME, facilitating more efficient and uniform processing.

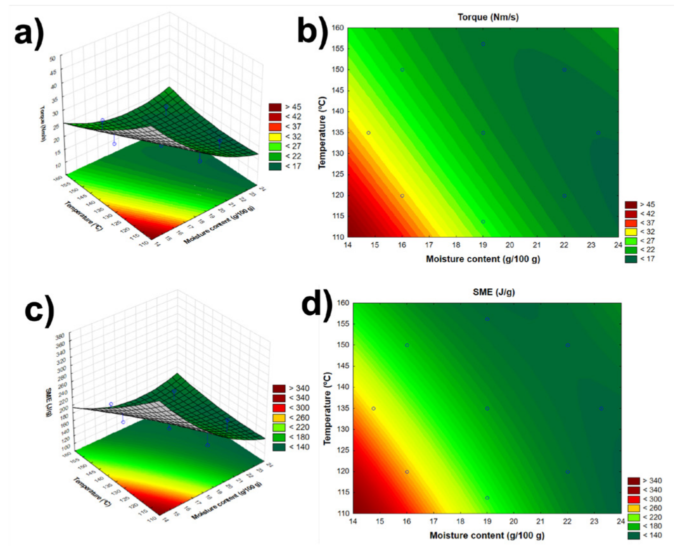

Figure 2: Response surface and contour plots showing the effect of temperature and moisture content on (a) and (b) torque, and (c) and (d) specific mechanical energy (SME).

Expansion index (EI), bulk density (BD), and Maximum compression breaking force (MCBF)

The regression analysis (Table 4) indicated that the linear effect of moisture content in the feed was the primary factor that significantly influenced (p < 0.05) the EI. In contrast, quadratic effects, the interaction between process variables (temperature and moisture), and the linear effect of temperature did not show statistically significant effects on this response. Intermediate temperatures (125–145 °C) and moisture contents between 16 and 18 g/100 g yielded the highest EI values (1.0 to 1.1), as shown in the response surface plots (Figure 3a) and contour plots (Figure 3b). The model exhibited a coefficient of determination (R^2) of 0.75. The negative effect of moisture content on EI demonstrates that higher water levels in the mixture reduce the expansion capacity of the extrudate. This behavior has been reported by Inayah *et al*. (2024), who observed that elevated moisture levels produce denser, less expanded extrudates in corn grit–sago flour blends. Similarly, Vivar-Vera *et al*. (2023) documented an inverse relationship between moisture and expansion in extrudates made with pineapple by-products and corn flour, reflecting a trade-off between these variables. This phenomenon is explained by the plasticization of the melt caused by excess water, which reduces dough elasticity and inhibits starch gelatinization (García-Domínguez *et al*., 2025). As a result, the final product is less expanded, denser, and mechanically firmer.

During extrusion, the abrupt pressure drop as the material exits the die promotes internal bubble formation due to water evaporation (García-Domínguez *et al*., 2025). However, at high moisture levels, viscosity decreases and bubbles tend to collapse, preventing effective expansion (Kamarudin *et al*., 2018; Kantrong *et al*., 2018).

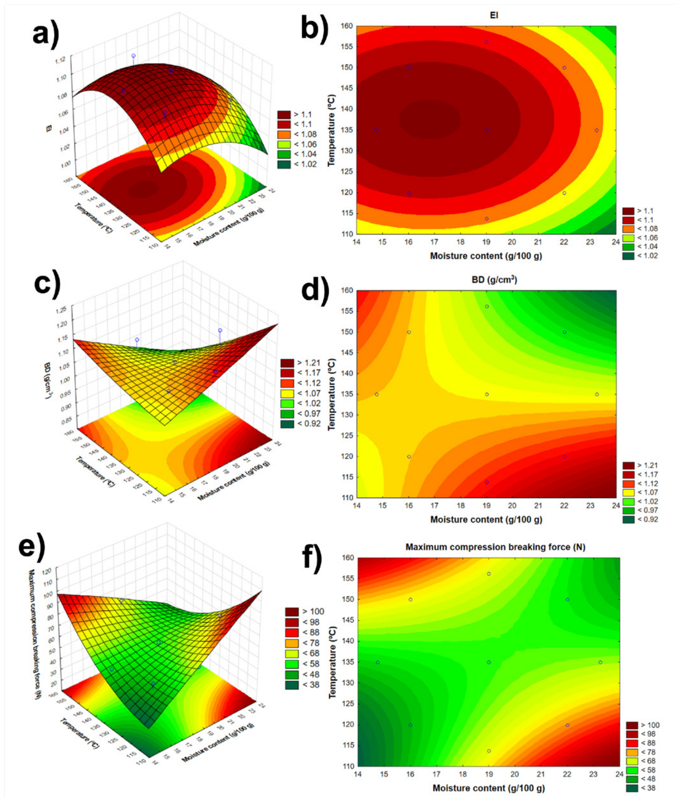

Figure 3: Response surface and contour plots showing the effect of temperature and moisture content on: (a) and (b) expansion index (EI), (c) and (d) bulk density (BD), and (e) and (f) maximum compression breaking force.

Regarding BD, no significant effects (p > 0.05) were observed for the independent variables, although the model exhibited a moderate coefficient of determination (R^2 = 0.64, Table 4), suggesting the possible influence of other uncontrolled factors. Figure 3c, d show that the highest BD values (1.07–1.21 g/cm^3) occurred with moisture contents between 20 and 24 g/100 g, while the highest temperatures (140–160 °C) yielded extrudates with lower density (0.92–1.02 g/cm^3). This behavior suggests that moisture promotes compaction of the feed matrix, enhancing cohesion among ingredients and resulting in denser extrudates (García-Domínguez *et al*., 2025). In contrast, low moisture levels may hinder starch gelatinization, while excessive moisture can lead to agglomeration issues or structural instability. Additionally, increasing temperature tends to enhance the plasticity of the material, promoting expansion and reducing product density, although it may also lead to nutrient degradation (Juárez-Barrientos *et al*., 2025).

As for MCBF, a significant effect (p < 0.05) of the moisture content-temperature interaction was identified, with a coefficient of determination of R^2= 0.78. The highest MCBF values (88–100 N) were observed under conditions of high moisture (20–24 g/100 g) and elevated temperatures (150–160 °C), as shown in Figure 3e, f. This parameter is essential for characterizing the mechanical strength and structural stability of extruded pellets, which directly impacts their handling, storage, and acceptance by animals. Moisture within that range tends to plasticize components such as starch and fiber, resulting in a denser and more resistant structure. Conversely, lower moisture levels may produce brittle extrudates, while excessive levels may weaken structural integrity due to pore formation (Juárez-Barrientos *et al*., 2025; Vivar-Vera *et al*., 2023). Temperatures in the 150–160 °C range promote starch gelatinization and partial protein denaturation, enhancing structural cohesion. Additionally, the presence of pineapple residues-rich in fiber, soluble sugars, and bromelain, encourages molecular interactions that reinforce pellet integrity (Vivar-Vera *et al*., 2023). Collectively, these results demonstrate that the significant interaction between moisture and temperature contributes to producing extruded feed with excellent mechanical properties, suitable for intensive beef cattle feeding systems. Moreover, the use of pineapple residues not only adds value to agro-industrial by-products but also enhances the structural functionality of compound feeds.

The water absorption index (WAI), water solubility index (WSI), and pH of extruded

The WAI and WSI provide critical information regarding the functionality of extruded products, as they are directly related to internal structure, starch gelatinization, and feed stability within the ruminal environment. In this study, the quadratic term of temperature had a significant negative effect ($p < 0.05$) on WAI, with a coefficient of determination of R^2=0.79 (Table 4). As shown in Figures 4a and 4b, the highest WAI values were observed at temperatures between 130 and 145 °C and moisture levels of 14–15 g/100 g and 22–24 g/100 g. This behavior suggests efficient starch gelatinization without excessive thermal degradation, a condition that favors the formation of a dense, cohesive matrix capable of retaining water. Additionally, these conditions intensify mechanical friction within the extruder barrel, increasing the internal temperature of the blend and enhancing its hydration capacity (Ding *et al*., 2005). The presence of fibers from pineapple residues may also contribute positively by acting as a structural framework and promoting water retention in the extrudate. This finding aligns with Tsagareishvili *et al*. (2019), who reported that low moisture content (~15%) in raw materials leads to more amorphous, dense, and cohesive structures after extrusion, resulting from limited gelatinization that enhances absorption properties.

Regarding WSI, a significant negative effect ($p < 0.05$) was identified for both the quadratic term of temperature and the temperature–moisture interaction, with a robust predictive model (Table 4). As shown in Figure 4c, d, the highest WSI values were observed under high-temperature conditions (140–160 °C) and low moisture content (14–18 g/100 g). This behavior can be attributed to the thermal degradation of structural components such as starches, leading to the formation of low-molecular-weight molecules that are water-soluble. Alam *et al*. (2016) reported that this phenomenon is characteristic of extrusion processes carried out at high temperatures and low moisture, where dextrinization and the formation of other soluble compounds are intensified. The composition of pineapple residues, rich in soluble sugars and dietary fiber, may enhance this effect under extreme thermal conditions. Hernández-Santos *et al*. (2021) noted that fibers derived from tropical fruits exhibit a high solubilization capacity when exposed to heat, which is consistent with the behavior observed here. However, it is important to note that although a moderately high WSI can facilitate rapid nutrient availability in animal feeding systems, excessively high values may compromise the structural integrity of the pellet and reduce its stability during handling and storage.

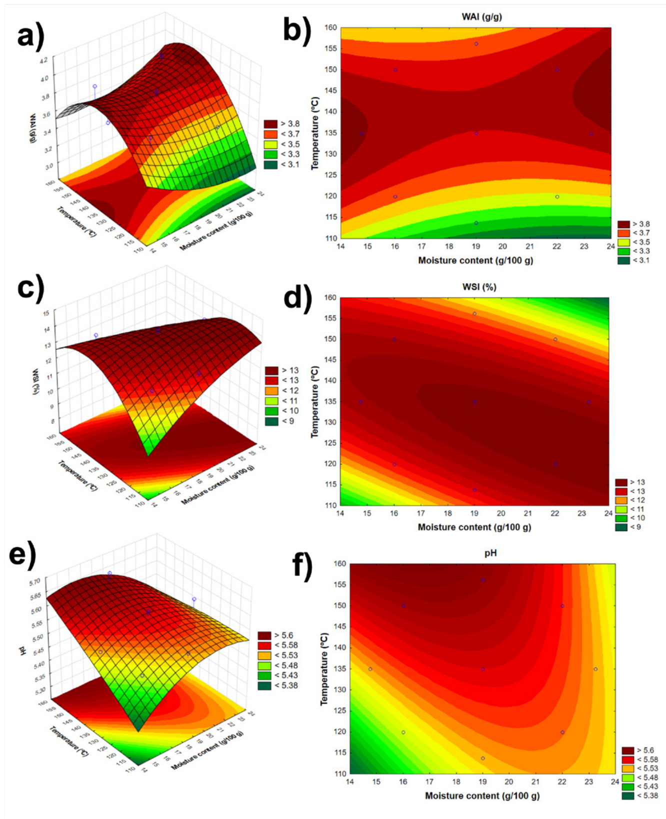

Figure 4: Response surface and contour plots showing the effect of temperature and moisture content on (a) and (b) water absorption index (WAI), (c) and (d) water solubility index (WSI), and (e) and (f) pH.

As for the pH of the extrudate, this parameter is particularly relevant due to its influence on microbiological stability, ruminal digestibility, and the physicochemical properties of the final product. In the present study, extrusion temperature had a significant positive linear effect ($p < 0.05$) on pH, with a coefficient of determination of R^2

= 0.72 (Table 4). Figure 4e, f show that the highest pH values were recorded at temperatures between 140 and 160 °C and moisture contents ranging from 14 to 21 g/100 g. This increase in pH can be attributed to the thermal degradation of naturally occurring acidic compounds in pineapple residues, such as citric, malic, and ascorbic acids. At elevated temperatures, these acids decompose, reducing their concentration in the final product and creating a less acidic environment. This phenomenon has been described by Alam *et al.* (2016), who noted that high-temperature extrusion can raise pH due to the loss of volatile acids and the formation of alkaline compounds derived from Maillard reactions and protein breakdown. Additionally, Robin *et al.* (2011) reported that in fiber-rich matrices such as tropical fruit residues, heat induces structural changes that release basic amines and peptides, contributing to an increase in pH. From a zootechnical perspective, a pH close to neutrality is desirable in cattle feed, particularly in ruminal systems, where extreme deviations can negatively affect the rumen microbiota and digestive efficiency.

Color parameters

The results presented in Table 4 indicate that temperature had a significant negative linear effect ($p < 0.05$) on lightness (L^*), while moisture content exhibited a significant positive linear effect. This trend is clearly illustrated in Figure 5a, b, where the highest L^* values were recorded under low-temperature conditions (110–150 °C), regardless of moisture level (14–24 g/100 g). The reduction in lightness with increasing temperature can be attributed to Maillard reactions, which are responsible for the formation of dark-colored compounds during intense heating of the ingredients (Alam *et al.*, 2016; Robin *et al.*, 2011). This behavior is consistent with other studies reporting L^* decreases in thermally treated extruded products because of caramelization and the formation of brown pigments via non-enzymatic reactions (Meng *et al.*, 2023).

Regarding the a^* parameter, which represents the intensity of red hues, a significant increase was observed with rising temperature, suggesting that elevated thermal conditions favor the formation or preservation of red-color-related compounds. This effect may be associated with both the thermal degradation of natural pigments such as carotenoids and the generation of colored compounds resulting from thermal reactions between proteins and reducing sugars (Juárez-Barrientos *et al.*, 2025; Vivar-Vera *et al.*, 2023). Figure 5c, d confirm this trend, with higher a^* values recorded at elevated temperatures (145–160 °C) and moisture levels between 19 and 24 g/100 g. García-Domínguez *et al.* (2025) and Brennan *et al.* (2011) reported that increasing extruder temperature leads to significant changes in phenolic compounds, suggesting that heat promotes the emergence or transformation of secondary pigments. In general, higher processing temperatures in extruded plant-based products tend to increase color intensity, especially red hues, due to thermal reactions generating phenolic and carotenoid-derived pigments.

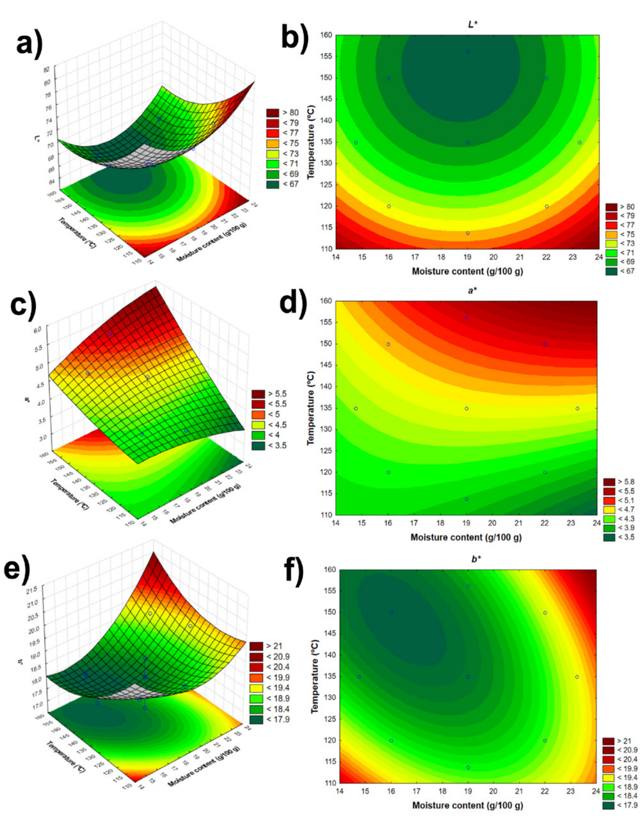

Figure 5: Response surface and contour plots showing the effect of temperature and moisture content on color parameters: (a) and (b) L^*, (c) and (d) a^*, and (e) and (f) b^*.

As for the b^* parameter, which corresponds to yellow coloration, a significant ($p < 0.05$), though less pronounced, effect was identified, primarily associated with moisture content (Table 4). The highest b^* values were observed in extrudates produced with high moisture levels (22–24 g/100 g), as shown in Figure 5e, f. This suggests that high moisture levels during extrusion favor the preservation or formation of yellow pigments, possibly derived from naturally occurring carotenoids in pineapple residues (Pélagie *et al.*, 2022). The combination of high temperature and moisture appears to enhance this color expression, underscoring the importance of controlling both parameters during processing to optimize the sensory properties of the final product. It is worth noting that the predictive models used to describe color parameter behavior showed high accuracy, with determination coefficients of R^2= 0.92 for L^*, R^2 = 0.95 for a^*, and R^2= 0.69 for b^*, supporting the statistical robustness of the analysis of extrusion effects on extruded feed coloration.

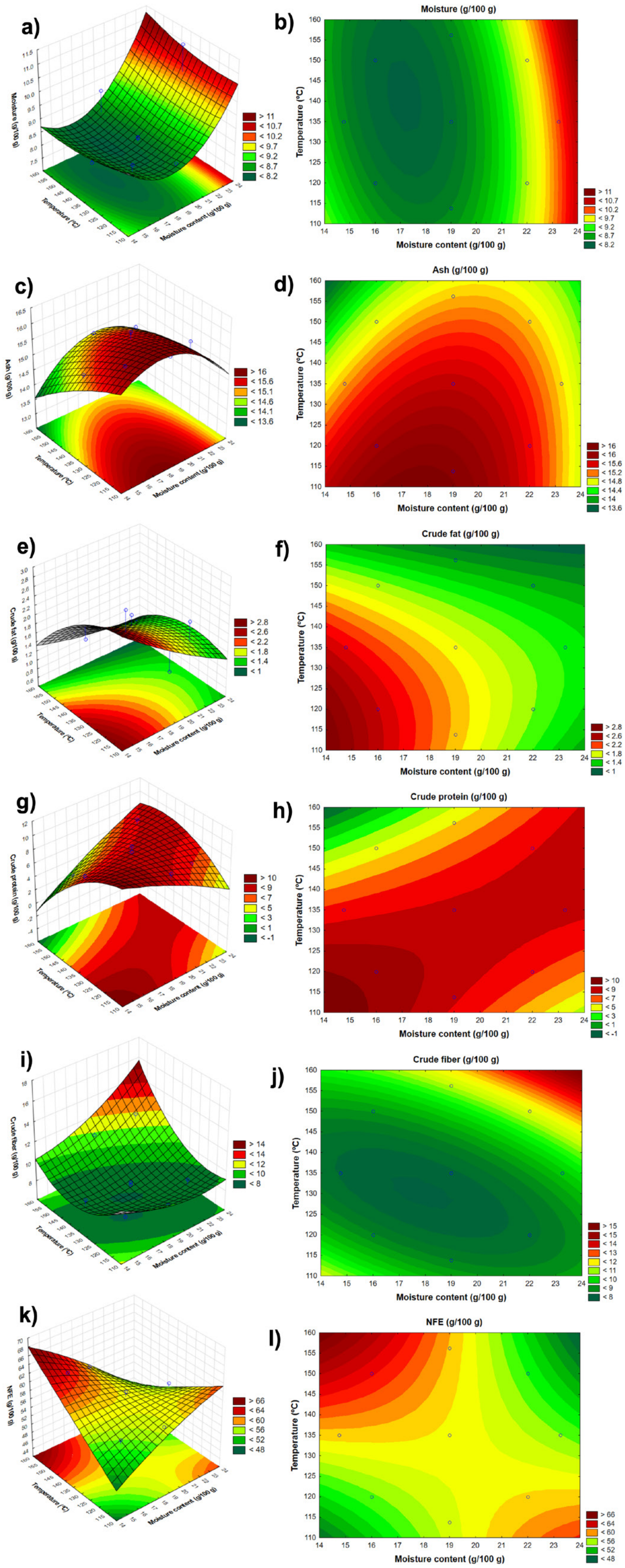

Figure 6: Response surface and contour plots showing the effect of temperature and moisture content on chemical composition: (a) and (b) moisture, (c) and (d) ash, (e) and (f) crude fat, (g) and (h) crude protein, (i) and (j) crude fiber, and (k) and (l) nitrogen-free extract (NFE).

Effect of temperature and moisture content on the chemical composition of the extrudates

Multiple linear regression analysis revealed that the moisture content of the extrudates increased significantly ($p < 0.05$) as a function of the initial moisture level of the feed mixture (Table 4). The coefficient of determination was moderate ($R^2 = 0.55$), indicating that approximately 55% of the variability in final moisture content could be explained by this variable. Figure 6a, b display an upward linear trend, confirming that the final moisture content is directly influenced by the initial water level, while temperature had minimal impact. This finding highlights the importance of precise moisture control during the pre-extrusion stage. Concerning ash content, temperature exhibited a significant negative linear effect ($p < 0.05$), with a coefficient of determination of $R^2 = 0.79$ (Table 4), indicating a good explanatory capacity of the model. As shown in Figure 6c, d, higher temperatures reduced ash content, likely due to the volatilization of heat-sensitive minerals during the extrusion process (Monti *et al.*, 2008). The optimal conditions to minimize this loss were identified between 120–130 °C and 16–18 g/100 g of initial moisture.

In terms of fat content, a significant negative linear effect of temperature ($p < 0.05$) was also observed, with a moderate coefficient of determination ($R^2 = 0.61$, Table 4). Figure 6e, f illustrate a progressive decline in fat content as both temperature and moisture increased during processing. This reduction may be attributed to the interaction between lipids and the carbohydrate–protein matrix under elevated thermal conditions, favoring partial fat encapsulation and limiting its extraction during analytical procedures (Strange and Schaich, 2000).

For protein content, temperature had a significant negative linear effect ($p < 0.05$), while the temperature–moisture content interaction showed a positive effect (Table 4). The model displayed high predictive accuracy ($R^2 = 0.87$). Figure 6g, h reveal that temperatures above 140 °C significantly reduced protein content, likely due to thermal denaturation and Maillard reactions. However, intermediate moisture levels (18–20 g/100 g) helped mitigate this loss, possibly by exerting a protective effect against thermal stress (Singh *et al.*, 2024; Sun *et al.*, 2023).

In the case of fiber content, both the linear and quadratic terms of temperature exhibited significant positive effects ($p < 0.05$), with an excellent model fit ($R^2 = 0.85$, Table 4). Figure 6i, j show that high temperatures (140–150 °C), combined with medium-to-high moisture levels (18–22 g/100 g), significantly increased the amount of fiber detected. This increase may result from the thermal transformation of structural polysaccharides into compounds more resistant to conventional fiber analysis methods (Robin *et al*., 2011). Furthermore, more complete starch gelatinization in the presence of elevated moisture may promote the formation of a matrix that encapsulates insoluble fibers, facilitating their retention and detection (Hernández-Santos *et al*., 2021).

As for nitrogen-free extract (NFE), a significant negative linear effect of moisture content was detected, along with a significant interaction effect between temperature and moisture (p < 0.05, Table 4), with a high coefficient of determination (R^2 = 0.90). Figure 6k,1 clearly show a decline in NFE levels under high-temperature conditions (140–150 °C) and moderate-to-high moisture (20–22 g/100 g). This reduction may be attributed to the gelatinization and thermal conversion of complex carbohydrates into simpler compounds such as dextrins and soluble sugars (Alam *et al*., 2016). This finding is particularly relevant, as it directly affects the energy availability and fermentability of the feed within the bovine rumen.

CONCLUSION

This study demonstrated the technical feasibility of formulating a balanced extruded feed for beef cattle using agro-industrial pineapple residues. The analysis of processing conditions revealed that both moisture content and temperature exerted a significant influence on the physicochemical properties of the final product. An intermediate moisture content (16–18 g/100 g) promoted expansion and improved the mechanical properties of the extrudate, while higher moisture levels increased bulk density and structural strength of the pellet, key attributes for handling and storage.

The optimal processing temperature range (140–150 °C) enhanced starch gelatinization, improved water absorption capacity, and induced desirable modifications in the protein and fiber structures of the feed. Overall, the findings indicate that the incorporation of pineapple agro-industrial residues not only enhances sustainability and adds value to the production process but also enables the development of extruded feeds with suitable nutritional and functional properties for intensive bovine production systems. This approach aligns with agricultural by-product valorization strategies under the circular economy framework.

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NOVELTY STATEMENT

This study is the first to explore how pineapple agro-industrial residues can be effectively used to formulate an extruded balanced feed for beef cattle. Unlike previous research focused only on their use as forage, this work shows that, by optimizing extrusion conditions such as temperature and moisture, it is possible to obtain pellets with strong structural integrity and valuable nutritional properties suitable for intensive feeding systems. Beyond improving feed efficiency, the study offers a sustainable alternative for managing agricultural by-products, providing new insights into how food waste can be transformed into high-value ingredients under a circular economy approach.

AUTHOR'S CONTRIBUTION

ER-F, BH-S, JMR-R and JGT-U: Conceptualization, data curation, formal analysis, investigation, methodology, software, writing-original draft; writing-review and editing.
JMJ-B, EJR-R, FA-G and VMM-V: Formal analysis, investigation, methodology, writing-original draft, writing-review and editing.
JR-M: Conceptualization, funding acquisition, methodology, project administration, resources, writing-review and editing.

Generative AI and AI-assisted technology statement

AI-assisted tools (ChatGPT) were used only to improve the clarity and language of the manuscript. The authors reviewed, validated, and take full responsibility for the content.

Conflict of interest

The authors have declared no conflict of interest.

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