Research Article

Cost-Effective Feed Formulation for Native Chickens: Integrating Fuzzy Linear Programming and Near-Infrared Spectroscopy in Small-Scale Production

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Abstract | The development of native chicken farming in rural Indonesia is constrained by high feed costs and the varying nutrient composition of locally available feed ingredients. Additionally, the specific nutrient requirements (NR) of native chickens remain insufficiently defined. This study integrates Fuzzy Linear Programming (FLP) and Near-Infrared Spectroscopy (NIRS) to address two uncertainties: variability in local feed composition and imprecise NR for native chickens. The chemical composition of corn, rice bran, and fishmeal was determined using NIRS, whereas other feed ingredients were analyzed through proximate analysis, atomic absorption spectrophotometry and literature studies. Feed formulation models were constructed at λ values of 0 (minimum NR) and 1 (meet maximum NR), with the FLP model identifying the most efficient formulation within these bounds. The optimal solution was obtained at $\lambda = 0.57$, producing a ration containing 17.87% crude protein and 2772 Kcal/kg metabolizable energy. This formulation met the optimum NR while reducing feed costs by 12% compared to $\lambda = 1$. Furthermore, the optimized ration decreased dependency on imported soybean meal by 40% by increasing the utilization of rice bran and palm kernel meal. Feeding trials conducted during the starter period demonstrated that chickens fed the $\lambda = 0.57$ ration exhibited growth performance and feed conversion ratios comparable to those fed the $\lambda = 1$ formulation. These findings suggest that FLP is a promising tool for managing uncertainty in feed formulation, supporting the development of cost-effective and nutritionally adequate diets within small-scale feed industries.

Keywords | Poultry, Animal feed, Spectroscopy, Near-infrared, Linear models

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INTRODUCTION

The development of native chicken farming in rural Indonesia strengthens local economies, improves food security, and preserves biodiversity by providing protein, generating rural income, creating jobs, and supporting cultural traditions (Asnawi *et al.*, 2023; Munawaroh *et al.*, 2021; Prabowo *et al.*, 2023). However, its sustainability is threatened by high dependence on commercial feed, which accounts for up to 70% of production costs and relies heavily on imported ingredients like soybean meal, burdening small-scale farmers financially (Akhadiarto, 2019). Studies show that partially replacing commercial feed with local ingredients such as corn and rice bran can maintain growth rates while increasing farmers' income (Winarti and Wiranti, 2016). Therefore, developing feeds based on local ingredients is essential to support native chicken farming.

However, implementing this approach faces challenges, particularly the high nutritional variability of local feed ingredients. Variations in regional agricultural practices and environmental conditions result in inconsistent nutrient profiles of ingredients such as corn, rice bran, and fishmeal, which can affect poultry growth and productivity (Akhadiarto, 2019; Huda *et al.*, 2024; Octavia and Mu'min, 2023). A preliminary study in West Sumatra, Indonesia, highlighted this issue, reporting that the protein content of corn ranged from 6.48% to 10.49% (mean 7.83%, SD 0.84%, CV 10.78%), rice bran from 5.38% to 12.37% (mean 8.68%, SD 1.60%, CV 18.43%), and fishmeal from 38.33% to 68.42% (mean 46.59%, SD 16.98%, CV 36.54%) (Adrizal and Andasuryani, 2023). Such variability complicates feed formulation for small-scale feed industries (SSFIs) in rural areas, as inconsistent nutrient content between batches undermines feed quality stability.

To ensure stable nutrient content in complete feeds, it is essential to analyse each production batch in small-scale feed industries (SSFIs). The conventional proximate analysis method, however, is time-consuming and costly (Adrizal and Andasuryani, 2023). As an alternative, near-infrared spectroscopy (NIRS) provides a faster and more cost-effective solution for evaluating feed nutrients (Adrizal *et al.*, 2007; Adrizal and Andasuryani, 2023; Mosher *et al.*, 2024). Nevertheless, the accuracy of NIRS predictions is subject to systematic and random errors, commonly expressed as the standard error of prediction (SEP), which reflects the deviation between predicted and actual values. Despite this limitation, NIRS remains a practical tool for real-time feed analysis, as supported by numerous studies. In a preliminary study (Adrizal and Andasuryani, 2023), the SEPs for protein, fat, crude fiber, calcium, and phosphorus were as follows: in corn, 0.24%, 0.16%, 0.11%, 0.21%, and 0.06%, respectively; in rice bran, 0.06%, 0.18%, 0.18%, 0.08%, and 0.02%; and in fishmeal, 3.59%, 0.12%, 0.59%, 0.05%, and 0.69%. These SEPs represent the uncertainty of NIRS predictions (±SEP), which was incorporated into the fuzzy linear programming (FLP) model as a tolerance range.

Another problem in formulating feed for native chickens in Indonesia is the uncertainty of their nutrient requirements (NR). Abun *et al.* (2018) reported that dietary protein levels ranging from 15% to 19% with a Metabolizable Energy (ME) range of 2,750 Kcal/kg to 2,950 Kcal/kg had no significant effect on the growth of native chickens during the starter period. The content of crude fat and crude fiber ranged from 6.19% to 7.01% and 3.97% to 4.89%, respectively (Abun *et al.*, 2018). The content of Calcium and phosphate ranges from 1.01%to 1.34% and 0.55%to 0.72%, respectively (Abun *et al.*, 2018). Starter diets for native chickens containing 19% protein with a Metabolizable Energy (ME) of 2,830 Kcal/kg and 20% protein with an ME of 2,904 Kcal/kg resulted in statistically insignificant differences in performance (Sinurat *et al.*, 2022). Due to limited information on the NR of native chickens in Indonesia, references are often based on the Regulation of the Minister of Agriculture of the Republic of Indonesia, Number 31/Permentan/OT.140/2/2014 for laying hens (Minister of Agriculture of Republic of Indonesia, 2014). According to this regulation, the nutritional guidelines for starter laying hens stipulate a minimum of 18% crude protein, a maximum of 7% crude fat, a maximum of 6.5% crude fiber, calcium levels between 0.9% and 1.2%, total phosphorus between 0.6% and 1%, and a minimum of 2600 Kcal/kg of Metabolizable Energy (ME). Given these conditions, there is no definitive standard for the NR of chickens in Indonesia. This lack of standardization poses significant challenges for SSFIs in formulating cost-effective feed that meets NR.

The conventional least-cost feed formulation method uses linear programming (LP) techniques. This approach is widely used in various livestock industries, including poultry farming, to optimize feed costs while meeting nutrient requirements (NR) (Pesti *et al.*, 2024). LP systematically balances costs and nutrients, ensuring economic efficiency and sustainability in feed formulation (Akintan *et al.*, 2024; O'Farrill, 2018; Omidiora *et al.*, 2013; Pesti *et al.*, 2024; Udo *et al.*, 2021). However, although LP is a powerful tool for optimizing feed formulation, its effectiveness is limited by uncertainty in model coefficients, particularly nutrient content.of feed ingredients, and constraints, such as the NR of poultry. In practice, these input parameters are rarely known with certainty due to analytical variation, seasonal changes in ingredient quality, and supply chain inconsistencies, especially in SSFIs (Malkawi *et al.*, 2014).

To address this limitation, mathematical tools have been developed to manage vagueness and uncertainty. Fuzzy theory has emerged as a widely recognized tool for representing uncertain data across various fields (Malkawi *et al.*, 2014). Research has developed calculation methods that incorporate fuzzy logic into LP, known as Fuzzy Linear Programming (FLP). FLP integrates fuzzy logic into LP to manage uncertainty and imprecision in decision-making scenarios. This approach is beneficial in real-world problems where parameters and constraints are not precisely known (Wang, 2022).

In contrast to traditional LP, which relies on fixed coefficients and sharp constraints, FLP introduces flexibility by modelling nutrient content and requirements as fuzzy sets, making it inherently more robust to input variability. This robustness is particularly advantageous in

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SSFIs where inconsistencies in nutrient profiles and limited laboratory access. By tolerating fluctuations in input values, FLP generates feed solutions that remain viable under uncertain conditions, offering a distinct advantage over LP in unstable environments.

This research examines the application of FLP in formulating native chicken feed at the starter period, where the nutrient content of some local feed ingredients, such as corn, rice bran, and fishmeal varies greatly over time and from different source locations. The feed industry in this case supplies these feed ingredients from different areas in West Sumatra Province, Indonesia; thus, nutrient content must be determined for each batch. Therefore, NIRS is used to predict nutrient content, providing data quickly and cost-effectively. The NR of chicken are also not known accurately. Given these conditions, further research on FLP is essential to support SSFIs in formulating complete native chicken feed during the starter period.

MATERIALS AND METHODS

Materials

The feed ingredients used in this study were sourced from West Sumatra, Indonesia. The feed ingredients included corn, rice bran, fishmeal, coconut meal, soybean meal, bone meal, and mineral mix. The nutrient content of feed ingredients was determined using Near-Infrared Spectroscopy (NIRS) for corn, rice bran, and fishmeal (Adrizal and Andasuryani, 2023). However, for palm kernel meal and soybean meal, proximate analyses were conducted in 2024 at the Laboratory of Animal Biotechnology, Faculty of Animal Science, Universitas Andalas, Padang, to measure crude protein, crude fat, and crude fiber; meanwhile, calcium and phosphorus were analyzed using the Atomic Absorption Spectrometry method. Metabolizable energy (ME) data are quoted from Lesson and Summers (2008) except for palm kernel cake quoted from Blair (2023). The nutrient contents and ME of feeds are presented in Table 1.

In Table 1, the two extreme scenarios in the FLP model arise from the uncertainty of nutrient predictions indicated by the SEP. When the predicted nutrient content is overestimated (predicted value + SEP), the feed formulation tends to use low-quality ingredients, which results in poor actual nutrient adequacy. This condition is represented by a fuzzy membership value of λ=0. Conversely, when the predicted nutrient content is underestimated (predicted value - SEP), the formulation relies heavily on high-quality ingredients in large quantities, which can lead to actual nutrient levels exceeding requirements. This condition is represented by λ=1. These two endpoints reflect the uncertainty inherent in NIRS predictions and define the bounds of the fuzzy optimization model.

In addition, the nutrient and metabolizable energy (ME) requirements themselves were categorized into two levels as shown in Table 2. A fuzzy membership value of λ = 0 corresponds to the minimum acceptable nutritional standards, whereas λ = 1 corresponds to the maximum recommended NR. These two aspects, namely the uncertainty of ingredient composition and the range of NR, are integrated into the FLP model to determine an optimal balance between cost efficiency and nutritional adequacy.

Mathematical model of fuzzy linear programming

Equation 1: The feed formulation at fuzzy membership λ = 0 represents the scenario with the lowest nutritional adequacy, corresponding to the minimum acceptable nutrient levels.

$$\textit{Minimize } Z_0 = 5800X_1 + 3500X_2 + 6000X_3 + 2800X_4 + 10000X_5 + 7200X_6 + 30400\,X_7.$$

Table 1: The nutrient contents of feed ingredients on as-fed basis.

No	Feed	Cost (IDR/kg)	Nutrient contents					ME (Kcal/kg)
			Crude protein (%)	Crude fat (%)	Crude fiber (%)	Calcium (%)	Total phosphorus (%)	
1	Corn	5800	7.80±0.24[1)]	4.61±0.16[1)]	1.63±0.11[1)]	0.86±0.21[1)]	0.25±0.06[1)]	3313[2)]
2	Rice bran	3500	8.53±0.06[1)]	6.31±0.18[1)]	14.00±0.18[1)]	0.08±0.02[1)]	1.06±0.21[1)]	1900[2)]
3	Fish meal	6000	51.56±3.59[1)]	5.22±0.12[1)]	0.59±0.05[1)]	3.91±0.69[1)]	2.37±0.33[1)]	2750[2)]
4	Palm Kernel Meal	2800	15.92[3)]	5.89[3)]	22.46[3)]	0.53[3)]	0.84[3)]	1759[4)]
5	Soybean meal	10000	48.79[3)]	0.74[3)]	4.93[3)]	0.39[3)]	0.20[3)]	2540[2)]
6	Mineral B12	7200				24.31[5)]	3.95[5)]	
7	Topmix	30400	0.06[6)]					

[1)] NIRS-predicted values (Adrizal and Andasuryani, 2023); standard error of prediction (SEP) shown as ± values; [2)] Leeson and Summers (2008), [3)] Results of chemical analysis at the Laboratory of Animal Biotechnology, Faculty of Animal Science, Universitas Andalas Padang 2024. [4)] Blair (2023), [5)] Packaging labels of Mineral B12 produced by PT Eka Farma; [6)] Packaging labels of Topmix produced by PT Medion Ardhika Bakti.

Table 2: Nutrient and metabolizable energy requirements are required for complete native feed during the starter period.

No	Nutrient (%) and ME (Kcal/kg)	Compliance level			
		λ =0	References	λ =1	References
1	Crude protein (minimum)	15	Abun *et al* (2018)	20	Sinurat *et al*. (2022)
2	ME (minimum)	2600	Minister of Agriculture of Republic of Indonesia (2014)	2900	Sinurat *et al*. (2022)
3	Crude fat (Maximum)	7	Minister of Agriculture of Republic of Indonesia (2014)	7	Minister of Agriculture of Republic of Indonesia (2014)
4	Crude fiber (Maximum)	6.5	Minister of Agriculture of Republic of Indonesia (2014)	6.5	Minister of Agriculture of Republic of Indonesia (2014)
5	Calcium (minimum)	0.9	Minister of Agriculture of Republic of Indonesia (2014)	0.9	Minister of Agriculture of Republic of Indonesia (2014)
6	Phosphor total (minimum)	0.55	Abun *et al* (2018)	0.55	Abun *et al*. (2018)

λ= 0 indicates minimally acceptable fulfilment of requirements; λ= 1 represents full fulfilment of requirements.

Subject to:

$$8.04X_1 + 8.59X_2 + 55.15X_3 + 15.92X_4 + 43.34X_5 + 0.00X_6 + 0.06X_7 \geq 15.00$$
$$3313X_1 + 1900X_2 + 2750X_3 + 1759X_4 + 2550X_5 + 0.00X_6 + 0.00X_7 \geq 2600$$
$$4.77X_1 + 6.49X_2 + 5.34X_3 + 9.81X_4 + 0.65X_5 + 0.00X_6 + 0.00X_7 \leq 7.00$$
$$1.74X_1 + 14.18X_2 + 0.64X_3 + 31.65X_4 + 4.39X_5 + 0.00X_6 + 0.00X_7 \leq 6.5$$
$$1.07X_1 + 0.37X_2 + 4.60X_3 + 0.31X_4 + 0.35X_5 + 24.31X_6 + 0.00X_7 \geq 0.90$$
$$0.31X_1 + 1.74X_2 + 2.70X_3 + 0.14X_4 + 0.37X_5 + 3.95X_6 + 0.00X_7 \geq 0.45$$
$$X_3 \leq 10.00\%$$
$$X_4 \leq 10.00\%$$
$$X_7 = 0.50\%$$
$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 = 100\%$$
$$X_1, X_2, X_3, X_4, X_5, X_6, X_7 \geq 0$$

Equation 2: Feed formulation under fuzzy membership λ = 1 represents a scenario in which the ration's nutritional composition is fully optimized, meeting all nutrient requirements perfectly.

$$Minimize\ Z_1 = 5800X_1 + 3500X_2 + 6000X_3 + 2800X_4 + 10000X_5 + 7200X_6 + 30400\ X_7$$

Subject to:

$$7.56X_1 + 8.47X_2 + 47.97X_3 + 15.92X_4 + 43.34X_5 + 0.00X_6 + 0.06X_7 \geq 20.00$$
$$3313X_1 + 1900X_2 + 2750X_3 + 1759X_4 + 2550X_5 + 0.00X_6 + 0.00X_7 \geq 2900$$
$$4.45X_1 + 6.13X_2 + 5.10X_3 + 9.81X_4 + 0.65X_5 + 0.00X_6 + 0.00X_7 \leq 7.00$$
$$1.52X_1 + 13.82X_2 + 0.54X_3 + 31.65X_4 + 4.39X_5 + 0.00X_6 + 0.00X_7 \leq 6.50$$
$$0.65X_1 + 0.35X_2 + 3.22X_3 + 0.31X_4 + 0.35X_5 + 24.31X_6 + 0.00X_7 \geq 0.90$$
$$0.19X_1 + 1.48X_2 + 2.04X_3 + 0.14X_4 + 0.37X_5 + 3.95X_6 + 0.00X_7 \geq 0.55$$
$$X_3 \leq 10.00\%$$
$$X_4 \leq 10.00\%$$
$$X_7 = 0.50\%$$
$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 = 100\%$$
$$X_1, X_2, X_3, X_4, X_5, X_6, X_7 \geq 0$$

Based on the results of Equations 1 and 2, the FLP model (0 ≤ λ ≤ 1) was developed to accommodate intermediate scenarios, as formulated in Equation 3.

Equation 3: This feed formulation approach seeks to maximize the fuzzy membership value within the range 0 ≤ λ ≤ 1, optimizing the balance between cost efficiency and nutritional adequacy by maintaining nutrient levels within tolerable limits.

Maximize λ

Subject to:

$$5800X_1 + 3500X_2 + 6000X_3 + 2800X_4 + 10000X_5 + 7200X_6 + 30400X_7 + (Z_1 - Z_0)\,\lambda \leq Z_1$$
$$7.80X_1 + 8.53X_2 + 51.56X_3 + 15.92X_4 + 43.34X_5 + 0.00X_6 + 0.06X_7 - 5.00\,\lambda \geq 15.00$$
$$3313X_1 + 1900X_2 + 2750X_3 + 1759X_4 + 2550X_5 + 0.00X_6 + 0.00X_7 - 300\,\lambda \geq 2600$$
$$4.61X_1 + 6.31X_2 + 5.22X_3 + 9.81X_4 + 0.65X_5 + 0.00X_6 + 0.00X_7 - 0.00\,\lambda \leq 7.00$$
$$1.63X_1 + 14.00X_2 + 0.59X_3 + 31.65X_4 + 4.39X_5 + 0.00X_6 + 0.00X_7 - 0.50\,\lambda \leq 6.50$$
$$0.86X_1 + 0.36X_2 + 3.91X_3 + 0.31X_4 + 0.35X_5 + 24.31X_6 + 0.00X_7 - 0.00\,\lambda \geq 0.90$$
$$0.25X_1 + 1.61X_2 + 2.37X_3 + 0.14X_4 + 0.37X_5 + 3.95X_6 + 0.00X_7 - 0.00\,\lambda \geq 0.45$$
$$X_3 \leq 10.00\%$$
$$X_4 \leq 1.00\%$$
$$X_7 = 0.50\%$$
$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 = 100\%$$
$$X_1, X_2, X_3, X_4, X_5, X_6, X_7, \lambda \geq 0$$

Z_0= total cost at λ=0, Z_1= total cost at λ=1, X_1=corn, X_2=rice bran, X_3=fish meal, X_4=palm kernel cake, X_5=soybean meal, X_6=Mineral B12, X_7=topmix, and λ = fuzzy membership value.

Feed treatment experimental design

This study was carried out in accordance with ethical guidelines for the use of experimental animals, as stipulated in Indonesian Law No. 18 of 2009 concerning Animal Husbandry and Animal Health, particularly Article 66, which regulates animal welfare. The chickens were housed under humane and appropriate conditions, with sufficient cage space, proper heating and lighting, and feed and water provided *ad libitum* without any restriction. No invasive procedures were performed during the experiment, and observations were limited to feed intake and body weight measurements.

The experiment was conducted in Sijunjung Regency, West Sumatra Province, Indonesia, where ambient temperature during the study period ranged from 23°C to 32°C, with relative humidity between 70% and 85%. The chicks were raised under controlled housing conditions. During the brooding period (0 to 6 weeks of age), the ambient temperature was gradually decreased from 32–34 °C in the first week to 21–24 °C by the sixth week to ensure optimal comfort and growth. Lighting was provided according to standard layer management practices, beginning with 22 hours of light per day during the first week, and gradually reduced to 12–14 hours by the sixth week.

The feed treatments were formulated using Fuzzy Linear Programming (FLP) models at different fuzzy membership levels: λ = 0: minimum nutrient content, λ = 1: maximum nutrient content, and 0 ≤ λ ≤ 1: fuzzy optimal solution. The experimental design was a completely randomized design with three treatments and five replications. All chickens were fed ad libitum and had free access to clean drinking water throughout the 6-week experimental period.

Body weights were measured at the beginning (day 0) and end (day 42) of the trial to determine final body weight, body weight gain, and feed conversion ratio (FCR). One-way analysis of variance (ANOVA) was employed to assess the effect of dietary treatments on growth performance parameters. Upon detecting significant differences, Tukey's HSD test was applied to determine which treatment groups differed significantly. The feed treatment experimental design is briefly summarized in Table 5.

RESULTS AND DISCUSSION

The fulfilment of nutrient and metabolizable energy (ME) requirements in native chickens was analysed using a fuzzy approach. In this approach, the degree of fuzzy membership (λ) ranges from 0 to 1, where λ = 0 indicates the minimum acceptable fulfilment of nutrient and ME requirements, and λ= 1 represents the maximum fulfilment of these requirements. Table 3 presents the fuzzy membership data for various levels of nutrient and ME requirement fulfilment in native chickens, which can be used to identify and optimize appropriate feeding formulas. This approach allows SSFIs to adjust feed more flexibly based on actual conditions and specific needs of native chickens, thereby enhancing efficiency and productivity of the farm.

Table 3: Complete feed formula for native chickens with various fuzzy memberships.

No.	Feed ingredients	Formula (%)		
		λ= 0	λ= 1	Fuzzy (λ= 0.57)
1	Corn	45.64	55.50	50.91
2	Rice bran	37.97	9.10	16.07
3	Fish meal	10.00	10.00	10.00
4	Palm Kernel meal	5.89	1.38	8.71
5	Soybean meal	0.00	23.11	13.82
6	Mineral B12	0.00	0.42	0.00
7	Top mix	0.50	0.50	0.50
8	Amount	100.00	100.00	100.00
9	Price (IDR/Kg)	5317	6669	5892
	Nutrient and ME contents			
10	Crude protein (%)	15.00	20.00	17.87
11	ME (Kcal/kg)	2659	2900	2772
12	Crude fat (%)	5.21	3.82	4.83
13	Crude fiber (%)	6.50	3.61	6.50
14	Calcium (%)	1.11	0.90	0.96
15	Phosphor (%)	1.09	0.55	0.69

Table 3 shows that the optimal membership value of λ = 0.57 was obtained by solving Equation 3, which represents a compromise between the optimistic (λ = 1) and pessimistic (λ = 0) scenarios. This value corresponds to the maximum feasible membership degree, indicating the best trade-off between cost efficiency and nutritional adequacy under fuzzy conditions. This λ value was not selected arbitrarily as a midpoint, but was obtained through optimization of the FLP model in Equation 3, which maximizes the fuzzy membership function under cost and nutrient constraints. At λ = 0.57, the total feed cost is relatively low, achieving a 11.65% cost reduction compared to the λ = 1 scenario.

Although the nutrient and metabolizable energy (ME) contents are lower than those in the λ = 1 formulation, the nutritional requirements are still adequately fulfilled. The crude protein content of 17.87% and ME of 2772 kcal/kg fall within the acceptable NR range (Abun *et al*., 2018). According to Abun *et al.* (2018), crude protein levels between 15% and 19% in native chicken diets did not significantly affect growth performance during the starter period. The study also reported that ME levels ranging from 2750 to 2950 kcal/kg had no significant impact on growth. These findings are further supported by the Minister of Agriculture of the Republic of Indonesia (2014), which stipulates that the minimum ME requirement for laying hens in the starter phase is 2600 kcal/kg. In addition, the crude fat, fiber, calcium, and phosphorus levels also meet the minimum standards set by the same regulation. Therefore, despite having slightly lower nutrient levels than the λ = 1 formula, the feed formulation with a fuzzy membership value of 0.57 is considered more optimal due to its balanced nutritional adequacy and cost-effectiveness.

The cost analysis revealed a significant economic benefit using the FLP formulation at λ = 0.57. Specifically, the cost was reduced by approximately 12%, calculated from the difference between the highest-cost formula (λ = 1) at IDR 6,669/kg and the optimized fuzzy formula (λ = 0.57) at IDR 5,892/kg (Table 3). This demonstrates that the fuzzy formulation effectively balanced nutritional adequacy with cost efficiency, making it a financially viable option for small-scale poultry producers.

Another advantage of the fuzzy formulation (λ = 0.57) is the increased reliance on locally available feed ingredients, thereby reducing the need for imported components such as soybean meal. In this formulation, soybean meal inclusion was reduced from 23.11% to 13.82% (–40.2%), while rice bran was increased from 9.10% to 16.07% (+77%) and PKM from 1.38% to 8.71% (+530%). Despite these shifts in ingredient composition, feed intake, growth performance, and feed efficiency were maintained at levels comparable to the λ = 1 group, indicating that PKM at 8.71% did not adversely affect palatability or growth. This finding is consistent with the recommendations of Leeson and Summers (2008), who suggested a maximum of 20% rice bran for chicks up to 8 weeks of age, and with Abdollahi *et al.* (2016), who reported that PKM can be included up to 16% in broiler diets without negative effects. However, nutrient digestibility, gut morphology, and gut health markers were not directly assessed in this study, which could have provided deeper insight into potential subclinical impacts of PKM's anti-nutritional factors, such as λ-mannans. Future studies are recommended to include these parameters to more thoroughly evaluate the safety and nutritional adequacy of PKM at the inclusion levels used here.

Table 4: Range of nutrient content of complete feed.

Nutrients and ME	Formula		
	λ=0	**λ=1**	**Fuzzy (λ=0.57)**
Crude protein (%)	14.02-15.00	20.00-21.00	17.38-18.36
ME(Kcal/kg)	2659	2900	2772
Crude fat (%)	4.91-5.21	3.82-4.06	4.70-4.95
Crude fiber (%)	6.25-6.50	3.61-3.77	6.41-6.59
Calcium (%)	0.77-1.11	0.90-1.27	0.78-1.14
Phosphor total (%)	0.88-1.09	0.55-0.70	0.60-0.77

Table 5: Summary of the experimental design.

No	Experimental description	Details
1	Experimental animals	Unsexed day-old chicks
2	Breed	Kampung Unggul Balitnak (KUB)
3	Initial body weight	26.54±2.63
4	Number of chickens	150
5	Number of treatments	3
6	Replications per treatment	5
7	Chickens per replication	10
8	Total cage	15
9	Cage dimensions (cm)	150 × 75 × 75
10	Experimental design	Completely randomized design (CRD)
11	Location	Sijunjung Regency, West Sumatra Indonesia
12	Ambient temperature	23-32^{0}C
13	Relative humidity	70%-85%
14	Brooding temperature range (week1-6)	32-34 °C (week 1) to 21-24^{0}C (week 6)
15	Lighting schedule (week 1-6)	22 h (week 1) to 12 h (week 6)
16	Feeding system	Ad libitum
17	Drinking system	Free access to clean water
18	Feed treatments	Feed formula at λ=0, λ=1 and 0≤λ≤1 (FLP-base)
19	Observation period	0 to 6 weeks (42 days)
20	Performance indicators	Feed consumption, final body weight, body weight gain and feed conversion ratio
21	Statistical analysis	One-way ANOVA, Tukey's HSD test

The nutrient content in Table 3 is not absolute, as the values predicted by NIRS for corn, rice bran, and fishmeal contain errors indicated by the SEP. Therefore, the NR may not be fulfilled. Table 4 presents the complete feed nutrient content of three types of feed formulas based on fuzzy membership values λ= 0, λ= 1 and λ= 0.57 where at λ = 0, the nutritional requirements are minimally fulfilled. In contrast, λ = 1 indicates that all nutritional requirements are fully satisfied.

Table 4 shows that the feed formula's nutrient at λ = 0.57 still meet the requirements, even though it is assumed that the nutrient content of the feed ingredients is lower, namely the estimated value minus the SEP. The complete feed's protein content, at a minimum of 17.38%, meets the requirement of at least 15% as stated in (Abun *et al*., 2018). The crude fat, crude fiber, calcium, and phosphorus content is within the tolerance limit (Minister of Agriculture of Republic of Indonesia, 2014).

The effect of feed formula on the feed intake of native chickens is presented in Figure 1. Feed intake differed significantly among treatments (p = 0.04). Post-hoc analysis showed that chickens fed diets formulated with λ= 1 and λ= 0.57 had significantly higher feed intake compared to those fed the λ= 0 diet. However, no significant difference was observed between the λ= 1 and λ= 0.57 groups. These findings indicate that chickens tend to consume more feed when offered diets formulated to fully meet nutrient requirements (NR), likely due to improved palatability and a more balanced nutrient composition.

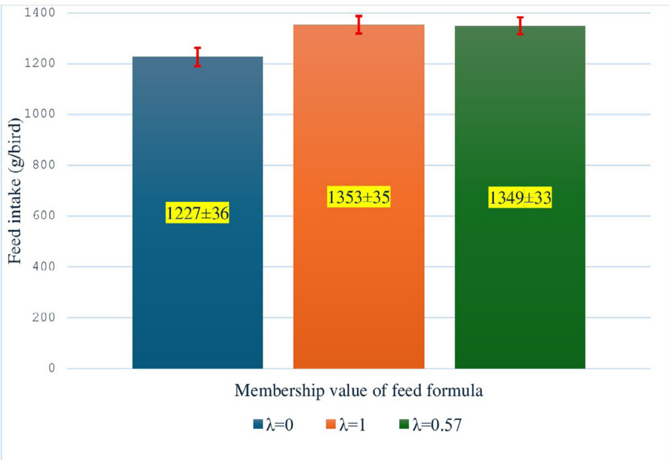

Figure 1: Feed intake of KUB chickens over 6 weeks on diets formulated with fuzzy membership values of λ = 0, λ = 1, and λ = 0.57.

The effect of feed formula on the final body weight of native chickens is presented in Figure 2. A highly significant difference was observed among treatments (p = 1.98 × 10^{-9}). Chickens fed the λ= 1 formula achieved the highest final body weight, followed by those fed the λ= 0.57 formula, while the lowest weight was recorded in chickens fed the λ= 0 formula. The higher final body weight observed in chickens receiving the λ= 1 diet reflects the positive impact of providing a diet that fully meets the optimal NR during the starter period. The λ= 0.57 formula, which provided intermediate nutrient levels, also proved effective in supporting satisfactory growth, as no statistically significant difference in final body weight was observed between the λ= 1 and λ= 0.57 groups.

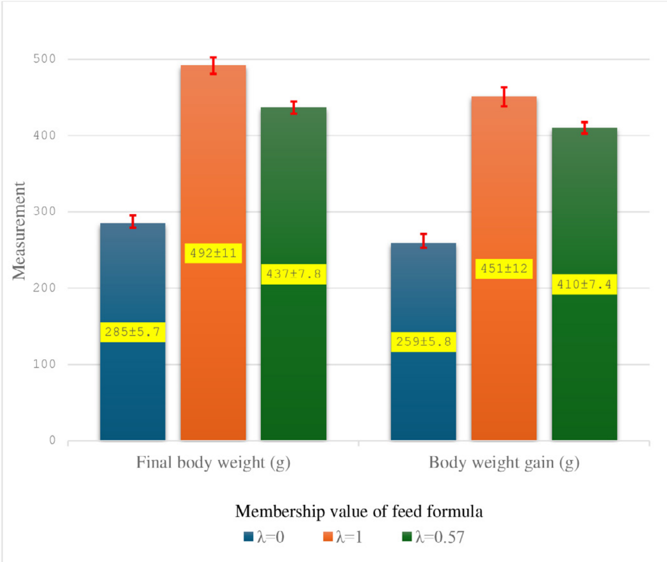

Figure 2: Final body weight and body weight gain of KUB chickens fed diets formulated with fuzzy membership values of λ = 0, λ = 1, and λ = 0.57 after 6 weeks.

Similarly, the pattern of body weight gain followed the same trend, as shown in Figure 2. A highly significant difference was observed among treatments (p = 8.67 × 10λ^{9}). Chickens fed the λ = 1 formula exhibited the highest weight gain, which was significantly greater than that of chickens fed the λ = 0 formula. The λ = 0.57 formula supported moderate growth performance; although the numerical weight gain in the λ = 0.57 group was slightly lower than in the λ = 1 group, the difference was not statistically significant.

Feed efficiency, measured as the feed conversion ratio (FCR) and shown in Figure 3, differed significantly among treatments (p = 1.69 × 10^{-6}). Chickens fed the λ = 1 and λ = 0.57 formulas showed significantly better FCRs than those fed the λ = 0 formula, formulated to meet only the minimum acceptable nutrient levels. Although the FCR of chickens fed the λ = 0.57 formula was slightly higher than that of chickens fed the λ = 1 formula, the difference between these two treatments was not statistically significant. This suggests that the fuzzy formulation (λ = 0.57) maintains feed efficiency comparable to the fully adequate diet (λ = 1), and markedly improves over the minimum-level diet (λ = 0).

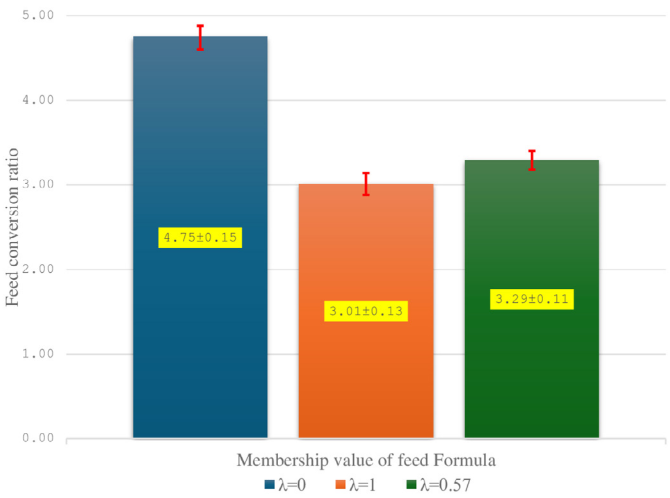

Figure 3: Feed conversion ratio of KUB chickens fed diets formulated with fuzzy membership values of λ = 0, λ = 1, and λ = 0.57 after 6 weeks.

The results of the feed treatment experiment further reinforce the conclusion that the λ = 0.57 formulation is the most optimal. Chickens fed with this ration exhibited statistically comparable performance to those receiving the λ = 1 formulation across all key biological parameters, including feed intake, weight gain, and feed conversion ratio. The absence of significant differences between the two groups indicates that, despite its lower nutrient density and reduced cost, the λ = 0.57 feed formula adequately met the nutritional requirements of native chickens during the starter period. These outcomes provide strong empirical validation that λ = 0.57 represents a biologically and economically optimal solution, thereby confirming the effectiveness and real-world applicability of the FLP model for small-scale poultry feed formulation.

It is important to note that the λ = 0.57 solution was derived based on ingredient prices and nutrient compositions at the time and location of the study. Variability in feed formulation needs can arise both from temporal changes, such as seasonal fluctuations and market price dynamics, and from spatial differences in ingredient availability and quality across regions. The FLP model is inherently designed to accommodate such variability by updating its inputs, including current ingredient prices and nutrient profiles. While the specific λ= 0.57 solution applies to the conditions in West Sumatra, the FLP model itself is adaptable and can be applied in other regions with different ingredient profiles. For example, in regions where cassava or other locally abundant ingredients are more prevalent than corn, the model can incorporate these alternative inputs and determine a new optimal λ value appropriate to the local context.

The λ= 0.57 formulation reduced feed costs by approximately 12% per kilogram of feed compared to the λ= 1 formulation, while maintaining statistically similar production performance. Although chickens fed the λ= 0.57 diet showed slightly lower final body weight and weight gain, these differences were not significant and remained within acceptable biological limits. A more detailed economic analysis, however, showed that the feed cost per kilogram of weight gain was only about 3.1% lower with the λ = 0.57 formulation (IDR 19,386/kg gain) compared to the λ = 1 formulation (IDR 20,007/kg gain). This modest saving can still improve profitability in small-scale production systems, where profit margins are narrow and feed is the largest cost component. Moreover, the λ = 0.57 formulation reduces reliance on imported soybean meal by increasing the use of locally available ingredients, which enhances sustainability and resilience of the feed supply. This trade-off between slightly reduced growth and better cost efficiency can therefore be economically favorable in the context of small-scale farming.

Based on the final body weight, the feed formulated using the FLP approach with λ = 0.57 achieved comparable performance. A study by Erwan *et al.* (2023) evaluated the growth performance of KUB chickens fed different rations over a six-week period. The treatments included 100% commercial feed, 95% commercial feed + 5% dry grated sago, 90% commercial feed + 10% dry grated sago, and 85% commercial feed + 15% dry grated sago. The final body weights obtained were 455.5, 401.6, 421.6, and 418.2 g/bird, respectively. These results indicate that the performance of chickens fed the FLP-based diet falls within the range of outcomes reported for birds receiving high levels of commercial feed, suggesting its potential as a cost-effective alternative.

These comparisons underscore the advantage of using FLP in feed formulation to balance nutrient adequacy and ingredient uncertainty, especially in small-scale or rural production systems. This is in line with the opinion of previous researchers (Nasseri and Darvishi, 2018) who stated that in certain countries it is difficult to meet nutrient needs perfectly, due to limited feed ingredients, so FLP provides an opportunity for the feed industry to formulate feed at certain intervals.

This study was conducted during the starter phase of native chickens, which are commonly raised as dual-purpose but predominantly developed for egg production. Although the evaluation was limited to early growth performance, the comparable outcomes between the λ = 0.57 and λ = 1 formulations suggest that the optimized fuzzy-based diet is capable of supporting proper skeletal and physiological development during this critical period. Adequate nutrition in the starter phase has been shown to influence the subsequent development of the reproductive system and long-term productivity in layer-type native chickens (Leeson and Summers, 2008; Sinurat *et al*., 2022). Therefore, the satisfactory performance observed in this phase indicates that the λ= 0.57 formulation has the potential to support continued growth and production in the grower and laying phases. Further research is recommended to apply the FLP approach in these later stages, thereby evaluating its effectiveness throughout the entire production cycle of native chickens.

This study has limitations related to both the NIRS method and the fuzzy linear programming model. The accuracy of NIRS predictions depends on the calibration model, which may not fully represent the variability of local feed ingredients. It is also less reliable for minor nutrients and sensitive to sample conditions such as moisture and particle size. Additionally, the FLP model is based on mathematical assumptions, especially in determining fuzzy membership values that do not fully describe real-world conditions. These limitations must be taken into account when applying the approach in a wider environment either in different locations or for application to other birds.

In addition to these methodological considerations, it is also important to address concerns regarding the environmental implications of ingredient choices in the optimized formulation. Although palm kernel meal is produced in the context of oil palm plantations, it is a by-product of palm oil extraction. Therefore, its inclusion in poultry feed does not drive land-use change or deforestation but rather utilizes an existing industrial by-product, contributing to resource efficiency and sustainability. Nevertheless, future development of the FLP model could incorporate environmental parameters, such as land-use impact or carbon footprint, as additional constraints to further enhance the sustainability of feed formulations.

The FLP model accommodates nutrient variability by integrating SEP margins into the formulation scenarios. In this approach, λ = 0 corresponds to predicted nutrient values plus SEP, while λ = 1 corresponds to predicted values minus SEP, defining the bounds of possible formulations. The optimal λ is determined as a compromise within this range, balancing cost efficiency and nutritional adequacy.

However, the relatively high SEP observed for fishmeal protein (3.59%) introduces greater uncertainty compared to other ingredients. This uncertainty can influence the outcomes of the optimization process, particularly when fishmeal contributes substantially to the dietary protein supply. Therefore, routine validation of NIRS-predicted values using wet chemistry methods is recommended, especially for fishmeal and other critical ingredients, to improve calibration accuracy and strengthen the reliability of FLP-based feed formulations. Such cross-validation is particularly important when ingredients are sourced from new suppliers or when significant variation is detected in NIRS readings.

Although the λ = 0.57 formulation was identified as optimal under current cost and nutrient variability conditions, the FLP model is designed to dynamically accommodate future fluctuations. Therefore, the optimal λ value may change depending on the prevailing data. By updating the model with current feed ingredient prices and nutrient profiles, small-scale feed industries (SSFIs) can re-optimize their feed formulations to maintain both nutritional adequacy and economic efficiency under changing market or seasonal conditions. In each formulation, the input data, including the current prices and nutrient content of the feed ingredients, are updated to reflect the most recent conditions. This ensures that the FLP model produces a feed formula that remains relevant and economically viable. As a result, the optimal λ value is recalculated during each formulation process and may vary according to the current data, reflecting the best balance between cost efficiency and nutritional adequacy at that time.

The FLP model effectively addresses uncertainties in nutrient composition and requirements while assuming a linear relationship between nutrient inputs and outputs. While this assumption simplifies the complexity of biological responses, the model remains robust when additional nutritional criteria, such as essential amino acid requirements, are explicitly included as linear constraints. This approach allows the model to more accurately reflect the biological needs of poultry without departing from the linear programming framework. Such flexibility is particularly advantageous for small-scale feed industries (SSFIs) in rural areas, where nutrient content of locally sourced feed ingredients can vary substantially between production batches due to inconsistent agricultural practices and environmental factors. Nevertheless, future research could still explore the potential of non-linear or stochastic programming approaches, which may further refine feed formulations if more complex, non-linear biological response models become available.

Another limitation of this study is that the FLP model did not explicitly include amino acid profiles, such as methionine and lysine, which are essential for optimal growth and laying performance. Although the λ = 0.57 formulation met crude protein requirements, unbalanced amino acid ratios may impair long-term productivity. Therefore, future research should consider incorporating amino acid constraints into the FLP model to ensure more precise and biologically adequate formulations.

CONCLUSION

This study demonstrates that FLP is an effective approach for formulating native chicken feed under conditions of uncertainty in both nutrient content of local feed ingredients and NR. The optimal feed formula was obtained at a fuzzy membership value of λ= 0.57, which provided a balance between nutrient adequacy and economic efficiency. This formulation met the nutrient needs of native chickens during the starter period, with performance indicators comparable to the ideal formula (λ= 1), yet at a lower cost. Moreover, it promoted the use of local feed resources, reducing reliance on imported ingredients such as soybean meal.

These results confirm that integrating the FLP and NIRS approaches SSFIs to formulate flexible, cost-effective, and locally sustainable poultry rations, thereby supporting the development of native chicken farming in rural areas. However, the limited availability of NIRS equipment and formulation expertise in these regions highlights the crucial role of local universities. Their involvement is essential in providing centralized services, technical guidance and capacity building to ensure a stable and sustainable feed supply for native chicken production. In the future, the FLP model could be further enhanced by incorporating amino acid constraints, which would improve its precision and ensure more nutritionally balanced formulations. Additionally, if more complex biological response models become available, the integration of non-linear or stochastic optimization methods could be explored to further refine the model and accommodate the high batch-to-batch variability of local feed ingredients in small-scale rural feed industries.

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NOVELTY STATEMENT

This study integrates Fuzzy Linear Programming (FLP) and Near-Infrared Spectroscopy (NIRS) for native chicken feed formulation in a small-scale industry. This method is a new alternative to formulating more flexible feed in an uncertain atmosphere in rural poultry production.

AUTHOR'S CONTRIBUTION

Adrizal is responsible for conceptualizing the research, data curation, investigation, methodology, visualization, and writing and editing the article. Andasuryani participated in data curation, software, validation, and writing the original draft. Montesqrit is responsible for data curation, investigation, writing and editing the article. Maria Endo Mahata and Zurmiati contributed to the investigation, writing, and editing of the article. This article was written collaboratively; all authors played a role in data curation and finalizing the article for publication.

Generative AI or AI-assisted Technology Statement

The author(s) declare that no Genrative AI was used in the creation of this manuscript.

Conflict of interest

The authors have declared no conflict of interest.

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