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Valorization of fruit and vegetable wastes for sustainable poultry feed: Nutritional profiling and functional evaluation

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Abstract
The poultry industry is under increasing pressure to balance productivity with sustainability, animal welfare and environmental responsibility. Feed formulation remains the most critical factor influencing poultry performance and production costs, however conventional reliance on corn and soybean meal raises concerns of resource depletion, ecological impact, and competition with human nutrition. The investigate the nutritional potential of fruit and vegetable wastes (FVWs) including apple pomace, mango kernel, carrot pulp, potato peels, pea pods, and banana foliage as alternative feed resources for poultry. Physicochemical analysis revealed that FVWs-based feed exhibited pH (5.3-6.6), moisture content (9.7-12.6%), and water holding capacity values comparable to commercial diets, confirming its microbial stability and suitability for consumption. Biochemical profiling showed wide variation in holocellulose and lignin, with mango kernel presenting the highest levels, while carrot pulp and apple pomace contained lower lignin, favoring digestibility. Amino acid analysis highlighted carrot pulp and banana foliage as rich sources of threonine, leucine, phenylalanine, and tryptophan, complemented by lysine and methionine from apple pomace and mango kernel, suggesting that blended formulations can provide a balanced amino acid spectrum. Crude fiber analysis indicated carrot pulp (20.60%) and apple pomace (16.16%) as fiber-rich substrates, while FVWs-based feed contained higher fiber (11.00%) than both branded (7.90%) and unbranded feeds (9.90%), supporting digestive health and feed efficiency.

Keywords: Fruit and vegetable wastes, Poultry feed formulation, Amino acid profile, Crude fiber analysis, Sustainable livestock production

1. Introduction

The poultry industry plays a pivotal role in global food security, particularly in developing nations, by supplying protein rich meat and eggs. However, the sector faces mounting challenges in balancing the growing demand for poultry products with sustainability, animal welfare, and human health concerns (Hafez *et al.*, 2020) [1]. Feed formulation remains the most critical determinant of poultry performance, health, and environmental trace (Gržinić *et al.*, 2023) [2]. Conservative dependence on corn and soybean meal as primary feed ingredients has raised concerns regarding resource depletion, environmental degradation, and competition between human and animal nutrition (Giannenas *et al.*, 2017) [3]. These issues emphasize the importance of identifying alternative feed resources that are cost effective, nutritionally adequate and environmentally sustainable (Mariutti *et al.*, 2021) [4]. Fruit and vegetable residues (FVRs), generated as by-products during food processing and consumption, have recently gained consideration as potential feed ingredients. These residues include peels, seeds, pulp, and trimmings, which were traditionally discarded in landfills, contributing to greenhouse gas emissions and resource loss (Kumar *et al.*, 2020) [5]. Advances in biotechnology and nutrition science have highlighted their potential to enhance poultry diets while at the same time reducing environmental burdens (Zhu *et al.*, 2023) [6]. Incorporating FVRs into poultry feed align with circular economy principles, improves resource efficiency and offers economic advantages due to their low cost availability (Dao *et al.*, 2023) [7]. Nutritionally, FVRs are rich in proteins, carbohydrates, vitamins, minerals, antioxidants, and dietary fiber, which support immunity, gut health, and growth performance in poultry (Ikusika *et al.*, 2024) [8]. Nutrient composition of FVRs varies with crop type, processing methods, and seasonal availability, complicating feed standardization (Singh *et al.*, 2024) [9]. Anti-nutritional factors such as tannins and oxalates may also hamper nutrient absorption if not properly managed (Erdaw, 2023) [10]. The logistical issues in sourcing, handling, and processing residues limit their widespread adoption. Nevertheless, previous studies have demonstrated that FVRs can stimulate gut microbiota, enhance immunity, and improve growth performance in poultry (Mnisi *et al.*, 2022; Râpă *et al.*, 2024) [11, 12]. However, broad comparisons between FVR-based feeds and commercial diets remain scarce. The specified feed costs

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account for 60-70% of total poultry production expenses (Business Plans, 2024) [13], integrating FVRs into feed formulations offers a promising strategy to reduce costs, improve sustainability and enhance bird health. The present study addresses existing gaps by analyzing the nutritional properties of fruit and vegetable wastes, formulating optimized poultry feed and evaluating its effects on broiler growth.

2. Material and method

2.1. Raw feed material

The study was conducted at a poultry farm in Mundhal Khurd, Bhiwani District, Haryana, India, where broiler performance was evaluated using both prepared and commercially available feeds under controlled conditions. Fruit and vegetable wastes (FVWs) were sourced locally from markets, juice vendors and food courts. Specifically, apple pomace, mango kernels, and carrot pulp were collected from juice outlets; potato peels and pea pods from hotel kitchens; and banana foliage from fruit and vegetable markets (Figure 1).



Figure 1. A- Waste Pea Pod, B- waste of apple Pomace, C- Waste of Carrot Pomace, D- Waste of Potato Pomace, *E*- Grinding of pea pod waste, F- Powder form of pea pod, G-Formation of carrot Powder, H-Prepared Powder form of different waste, I- Powder store from future use

2.2 Preparation of fruit and vegetable wastes

Collected fruit and vegetable wastes were physically sort to remove non organic contaminants such as plastic and paper. The feed stocks were chopped into crude particles and then dried using a solar tunnel dryer, a cost effective method employing renewable solar energy to reduce moisture content. The dried materials were processed with a biomass shredder and grinder to achieve a uniform particle size of 1-2 mm (Figure 2). The resulting powders were stored in airtight, moisture free polyethylene bags until further use.



Figure 2. A-Local feed, B- Commercial feed, C- Prepared feed with Different concentration of fruit and vegetable waste, D- Different feeds store for analysis

2.3 Physical properties analysis of FVWs and poultry feed

The ph analysis of fruit and vegetable wastes (FVWs) and formulated poultry feeds were analyzed to estimate pH, moisture content and water holding capacity (WHC), as these parameters are closely linked to nutrient accessibility, microbial stability, preservation, and digestibility (Dias *et al.*, 2020) [14]. The pH of homogenized samples was measured using a calibrated digital pH meter, since optimal pH values are known to enhance nutrient digestion, palatability, and microbial safety in poultry diets (Adedokun *et al.*, 2019) [15]. Moisture content was determined gravimetrically by oven drying at 105 °C until constant weight, following established protocols that recommend an ideal range of 10-12% to minimize microbial contamination and spoilage (Ahmed *et al.*, 2022; Preethi *et al.*, 2021) [16, 17]. WHC was assessed by soaking a known weight of sample in distilled water, centrifuging, and calculating the retain water relative to dry matter, as this property directly influences feed texture, nutrient incorporation and gut health (Huting *et al.*, 2021) [18].

2.4 Biochemical compositional analysis of FVWs

Assessment of biochemical composition in fruit and vegetable wastes was determined for lignin, holocellulose (cellulose + hemicellulose), and ash content. Lignin was quantified using acid hydrolysis with 72% H_2SO_4 followed by dilution to 3% and reflux at 70-80 °C; the residue was filtered and weighed (Wise *et al.*, 1946) [19]. Holocellulose was estimated by treating oven dried substrate with sodium chlorite and glacial acetic acid under reflux until the material turned white, followed by filtration and drying to constant weight. Ash content was measured by incinerating samples at 450±10 °C for 5 h in a muffle furnace (Saini *et al.*, 2023) [20]. The percentage composition of each component was calculated using:

Component % = $(W_1 - W_2) \times 100\ W$

Where W_1 = Weight of crucible with residue, W_2 = Weight of empty crucible, and W = Weight of test specimen.

2.5. Estimation of amino acids in FVWs

Amino acid content of FVWs was analyzed at SFTS Laboratory Pvt. Ltd., Delhi, using HPLC (Agilent Infinity II 1260, USA) equipped with a VWD detector and C18 column (4.6×100 mm, 2.7 µm). Mobile phase A contained Na_2HPO_4 and $Na_2B_4O_7{\cdot}10H_2O$ (pH 8.2±0.2), while mobile phase B was acetonitrile: methanol: wa

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ter (45:45:10, v/v/v). Hydrolyzed samples (0.5 µl) were injected into a 5.0 µl loop and separated under a solvent gradient at 0.2 ml/min, with the column maintained at 40 °C. Retention times were compared with amino acid standards for identification and quantification.

2.6 Estimation of crude fiber content in FVWs

Crude fiber content of FVWs was determined using Soxhlet extraction following the FSSAI protocol for cereals and cereal products. Briefly, 2.5 g of powdered sample was defatted with petroleum ether, and then digested sequentially with H_2SO_4 and NaOH under reflux. The slurry was filtered, washed with hot water and ethanol, and the residue dried at 105 ± 3 °C for 6 h, followed by ashing at 575 ± 10 °C for 24 h in a muffle furnace. Crude fiber percentage was calculated using:

Crude fiber % $= C1 - C2\ M \times 100$

Where $C1$ = Weight of crucible with residue before ashing, $C2$ = Weight after ashing, M = Weight of moisture free sample.

3. Results

3.1. Physical properties analysis of different FVWs and poultry feed

The physical categorization of fruit and vegetable wastes (FVWs) discovered pH values ranging between 5.3 and 6.6, which fall within the optimal range reported for poultry feed (Cox *et al.*, 2013; Kim *et al.*, 2006) [21, 22]. Moisture content varied from 9.7% (carrot pulp) to 12.6% (banana foliage), aligning with the recommended 10-12% range for feed stability. Water holding capacity (WHC) showed important variation, with pea pods exhibiting the lowest value (53.6%) and carrot pulp the highest (88.3%) (Figure 3). The formulated FVWs based feed displayed a pH of 6.5, moisture content of 10.9%, and WHC of 76.2%, values comparable to commercial local (pH 6.1, moisture 11.2%, WHC 86.2%) and branded feeds (pH 6.1, moisture 10.5%, WHC 84.2%). These conclusion corroborate that FVWs based feed possesses physicochemical properties consistent with conventional diets, supporting its suitability as a sustainable alternative (Table 1).

Table 1. Physical properties of various fruits, vegetable wastes and poultry feed

Sample	Description	pH	Moisture content (%)	Water Holding Capacity (%)
Apple pomace	Brown granular powder	6.6	9.8	73.6
Mango kernel	Light green granular powder	5.3	10.4	78.9
Carrot pulp	Light red granular powder	6.2	9.7	88.3
Potato peels	Whitish granular powder	5.3	12.5	83.2
Pea pods	Light green granular powder	6.2	10.1	53.6
Banana foliage	Yellow granular powder	6.3	12.6	86.0
FVWs based feed	Light red granular powder	6.5	10.9	76.2
Commercial Local feed	Light red granular powder	6.1	11.2	86.2
Commercial branded feed	Light red granular powder	6.1	10.5	84.2

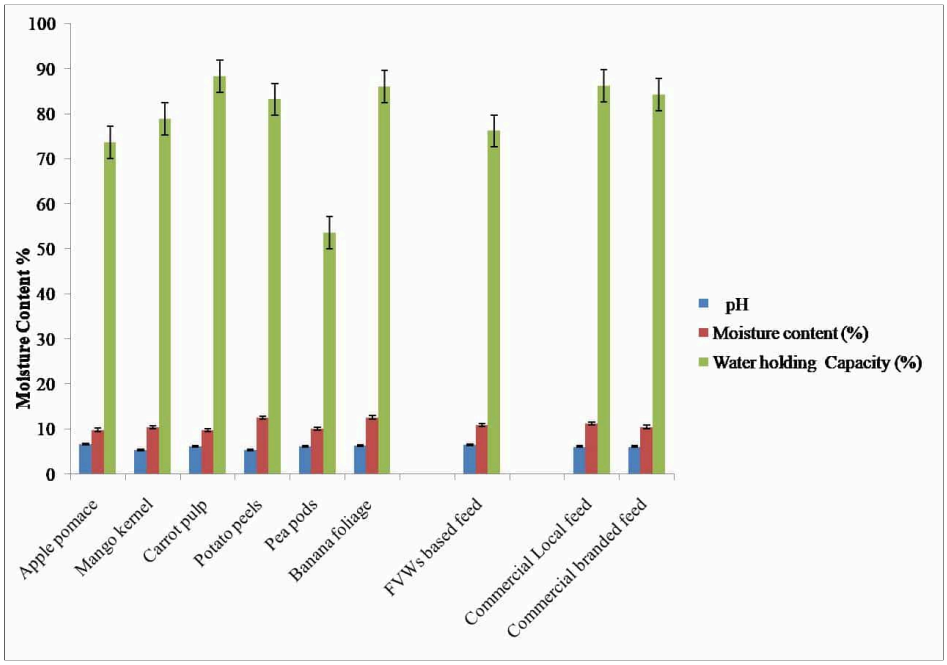


Figure 3. Comparative analysis of pH, moisture content, and water holding capacity of different fruit and vegetable wastes (FVWs) and poultry feeds.

3.2 Biochemical compositional analysis of FVWs

The biochemical analysis of fruit and vegetable wastes (FVWs) showed significant variation in holocellulose and lignin content. Mango kernel exhibits the highest holocellulose (76.81%) and lignin (21.46%), followed by potato peels (65.76% and 15.00%, respectively). Apple pomace contained moderate levels (53.12% holocellulose, 10.00% lignin), while carrot pulp had the lowest holocellulose (27.41%) and lignin (8.79%) (Figure 4). Banana foliage presented relatively low holocellulose (32.09%) but higher lignin (18.00%). These results highlight the compositional diversity among FVWs, indicating their differential potential as feed ingredients depending on nutrient and fiber requirements (Table 2).

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3.3 Estimation of amino acids

The amino acid analysis of fruit and vegetable wastes (FVWs) revealed notable variability among substrates. Carrot pulp was particularly rich in threonine (18.0 mg/100 g) and showed appreciable levels of tryptophan (3.7 mg/100 g). Banana foliage exhibited the highest concentrations of isoleucine (9.20 mg/100 g), leucine (10.31 mg/100 g), phenylalanine (9.50 mg/100 g), and tryptophan (7.30 mg/100 g), indicating its superior essential amino acid profile. Apple pomace contained moderate amounts of leucine (7.50 mg/100 g) and lysine (4.21 mg/100 g), while mango kernel was characterized by relatively high methionine (3.40 mg/100 g) and phenylalanine (6.0 mg/100 g). Potato peels showed balanced levels of lysine (4.32 mg/100 g) and tryptophan (8.2 mg/100 g). Pea pods were distinguished by their lysine content (7.4 mg/100 g). Overall, banana foliage and carrot pulp emerged as the most promising sources of essential amino acids, whereas apple pomace and pea pods provided moderate contributions (Table 3). WHO/FAO (NRC) guidelines require poultry diets to contain enough essential amino acids, with lysine (~1.0-1.3%), methionine+cystine (~0.5-0.7%), threonine (~0.7-0.8%), and tryptophan (~0.18-0.2%) as critical limits, while BIS (IS 1374:2024) standards likewise emphasize minimum thresholds for lysine, methionine, threonine, and valine to ensure balanced growth and feed efficiency.

Table 2. Biochemical Composition of Fruit and Vegetable Wastes (FVWs)

S. No.	Sample	Holocellulose (%)	Lignin (%)
1	Apple pomace	53.12	10.00
2	Mango kernel	76.81	21.46
3	Carrot pulp	27.41	8.79
4	Potato peels	65.76	15.00
5	Pea Pods	45.00	12.00
6	Banana foliage	32.09	18.00

Table 3. Amino acids profiling of selected fruits and vegetable wastes

Amino acids	Apple pomace (mg/100 g)	Mango kernel (mg/100 g)	Carrot pulp (mg/100 g)	Potato peels (mg/100 g)	Pea pods (mg/100 g)	Banana foliage (mg/100 g)
Threonine	2.81	-	18.0	2.80	-	2.81
Isoleucine	3.19	-	6.0	2.70	-	9.20
Leucine	7.50	6.2	4.0	5.02	-	10.31
Lysine	4.21	3.3	4.9	4.32	7.4	7.16
Methionine	1.30	3.40	2.0	1.90	1.8	2.52
Phenylalanine	3.20	6.0	2.8	2.73	-	9.50
Tryptophan	-	-	3.7	8.2	1.0	7.30
Tyrosine	-	-	3.0	-	-	-
Valine	2.31	4.20	4.0	3.09	-	2.01

3.4 Estimation of crude fiber content in FVWs

The fiber content varied significantly among the tested samples. Carrot pulp exhibit the highest fiber concentration (20.60%), followed by apple pomace (16.16%), indicating their potential as rich sources of dietary fiber. on the contrary, mango kernel (2.80%) and potato peels (2.20%) showed minimal fiber levels. Among feed formulations, the FVW-based feed recorded 11.00% fiber, which was higher than both unbranded (9.90%) and branded feeds (7.90%)

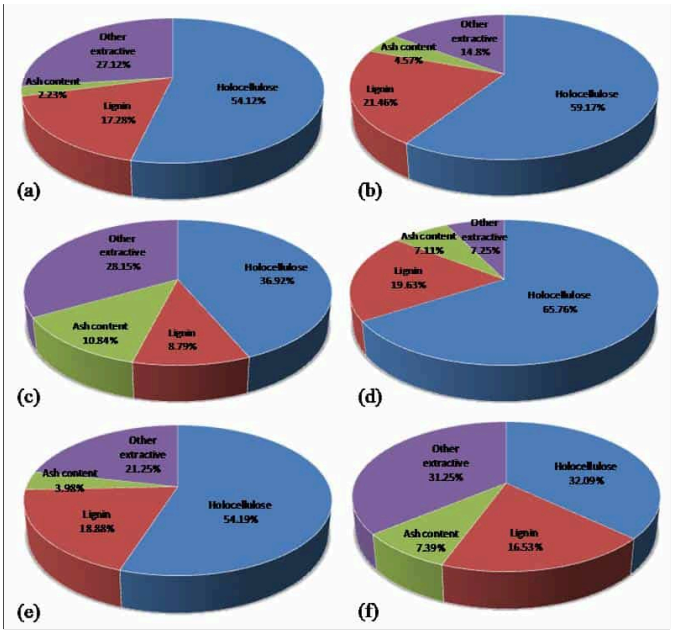


Figure 4. Biochemical compositional analysis of various FVWs. (a) Apple pomace, (b) Mango kernel, (c) Carrot pulp, (d) Potato peels, (e) Pea pods, and (f) Banana foliage.

3.5 Average Body (g) weight of chick broiler on different Feed

The prepared feed formulations showed values close to control (2042.28) and local feed (2010.02), with the blended FVWs feeds ranging between ~967-1767 depending on substrate; pea pod feed performed highest among residues (1767-1754), while mango and banana feeds were lowest (~977-999). The prepared feed (2014.28) was nearly equivalent to local feed, confirming FVWs blends provide comparable nutritional efficiency (Table 4).

Table 4. Average Body (g) weight of chick broiler on different Feed

Name of Prepared Feed	50 % Local +50% Prepared Feed	30 % Local +70% Prepared Feed	40 % Local +60% Prepared Feed
Pea Pod	1767.85	1743.02	1754.57
Potato Feed	1310.28	1276.85	1300.01
Banana feed	1009.73	986.75	999.42
Mango Feed	985.71	967.28	977.73
Apple Feed	1074.42	1049.71	1065.71
Carrot Feed	1138.28	1111.71	1126.42
Prepared feed		2014.28	
Control Feed		2042.28	
Local Feed		2010.02	

(continued on next page)

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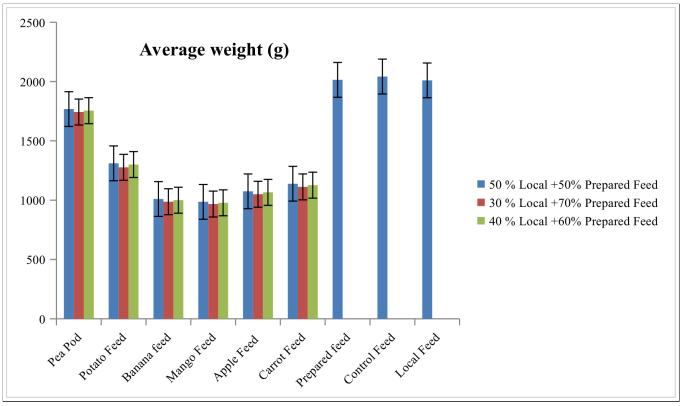


Figure 5. Comparative analysis of average body weight of broilers fed with different fruit and vegetable waste (FVW)-based feed formulations and commercial diets under varying proportions of local and prepared feed mixtures (50%, 60%, and 70%).

3.6 Economic and environmental impact assessment

Utilization of fruit and vegetable wastes (FVWs) in poultry feed reduce reliance on costly conventional ingredients such as corn and soybean meal, thereby lowering overall feed expenditure that accounts for 60-70% of production costs. Locally sourced residues like apple pomace and carrot pulp transform waste into value added feed, improving farm profitability and resilience against market fluctuations. Environmentally, FVWs divert agro industrial residue from landfills, mitigating greenhouse gas emissions and supporting circular economy principles. Processing through renewable energy methods, such as solar drying, further decreases the carbon footprint. By enhancing gut health and reducing reliance on synthetic additives, FVWs contribute to sustainable waste management and eco friendly poultry production.

4. Discussion

The fruit and vegetable wastes (FVWs) possess considerable nutritional potential and can be effectively utilized in poultry feed formulation. The physicochemical evaluation exposed that the pH, moisture content, and water holding capacity of FVWs based feed were similar to those of commercial diets, confirming its stability and suitability for poultry consumption. The pH values (5.3-6.6) fell within the optimal range for feed digestibility and microbial safety, while moisture content (9.7-12.6%) aligned with the recommended limits for feed preservation (Ahmed *et al.*, 2022; Preethi *et al.*, 2021) [16, 17]. The high water holding capacity observed in carrot pulp (88.3%) and banana foliage (86.0%) suggests improved feed texture and nutrient assimilation, which are beneficial for gut health and feed palatability (Kour *et al.*, 2025) [23]. Biochemical analysis indicates considerable variation in holocellulose and lignin content among FVWs, reflecting their diverse structural composition. Mango kernel exhibits the highest holocellulose (76.81%) and lignin (21.46%), implying a fibrous matrix that may influence digestibility. On the other hand, carrot pulp and apple pomace contained lower lignin levels, making them more suitable for inclusion in poultry diets where high fiber may limit nutrient absorption. The compositional diversity underscores the importance of balancing FVW proportions to optimize nutrient availability and feed efficiency (Siwach *et al.*, 2025) [24]. Amino acid profiling further highlighted the nutritional richness of certain residues. Carrot pulp and banana foliage emerge as superior sources of essential amino acids, particularly threonine, leucine, phenylalanine, and tryptophan, which are vital for protein synthesis and growth performance. The reasonable lysine and methionine levels in apple pomace and mango kernel complement these profiles, suggesting that a blended FVW formulation can provide a balanced amino acid spectrum. Such variety supports the concept of using mixed residues to achieve nutritional adequacy while minimizing dependence on conventional protein sources like soybean meal (Siwach, 2026) [25]. Crude fiber analysis revealed that carrot pulp (20.60%) and apple pomace (16.16%) are rich in dietary fiber, contributing to improved gut motility and nutrient absorption. The FVW based feed exhibited higher fiber content (11.00%) than unbranded (9.90%) and branded feeds (7.90%), indicating its potential to enhance digestive health and feed efficiency. Though, excessive fiber from certain residues, such as mango kernel and potato peels, may require controlled inclusion to prevent reduced nutrient digestibility (Siwach *et al.*, 2025) [24]. The FVWs can serve as sustainable, cost effective feed ingredients without compromising nutritional quality. Their incorporation supports circular economy principles by converting agro industrial waste into valuable feed resources, reducing environmental impact, and lowering production costs (Siwach, 2026) [25]. The study thus provides a scientific basis for integrating FVWs into poultry feed formulations, promoting resource efficiency and sustainable livestock production.

5. Conclusion

The fruit and vegetable wastes (FVWs) effectively incorporated into poultry feed formulations without compromise nutritional quality, as their physicochemical properties were comparable to commercial diets and their biochemical diversity provided balanced amino acid and fiber profiles that support digestive health and feed efficiency; though, limitations include seasonal variability in nutrient composition, lack of detailed quantification of anti nutritional factors, and logistical challenges in large scale collection and processing, while the absence of broiler performance data restricts practical validation; future research should therefore emphasize long term feeding trials assessing growth, immunity, and carcass yield, explore advanced processing methods such as fermentation or enzymatic detoxification to mitigate anti nutritional compounds, and conduct economic and life cycle assessment to quantify cost savings and environmental benefits, eventually enabling scalable integration of FVWs into poultry diets as part of circular economy practices for sustainable livestock production.

CRediT author contributions

Ankita Siwach:- Literature search, Writing - original draft, Data analysis, Software, Himanshu Malik:- Conceptualization, Data analysis, Anil Kumar :-Resources, Supervision, Visualization,

Conflict of interests

The authors declare that they have no conflict of interest with contents of this article.

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Availability of data and materials

All the data related to this article is provided within the manuscript.

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