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Evaluation of Agro-Industrial Tuber Peel Waste as an Alternative Energy Source in Livestock Diets: Implications for Nutritional Value, Caloric Density and Mineral Enrichment

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Abstract

This study investigated the nutritional, energetic, and mineralogical implications of replacing conventional maize with underutilized agro-industrial by-products in livestock rations. A 100% maize control diet (MFF) was evaluated against three experimental diets where maize was replaced at a 50% inclusion level with Irish potato peel meal (MPF), yam peel meal (MYF), or cassava peel meal (MCF). The partial substitution preserved total organic matter density across all formulations (>90%). However, the higher concentration of structural non-starch polysaccharides inherent to root and tuber epicarps significantly reduced carbohydrate and caloric delivery ($p < 0.05$). Nitrogen-free extract (NFE) decreased from 47.42% (control) to 38.92% (MYF), 38.05% (MCF), and 35.47% (MPF). The reduction in digestible carbohydrates led to a decrease in calculated metabolizable energy (ME) profiles, which fell from 10.43 MJ/kg (MFF) to 9.62 MJ/kg (MYF), 9.50 MJ/kg (MPF), and 8.72 MJ/kg (MCF) due to the dilution of physical fiber. Conversely, the incorporation of tuber wastes resulted in a substantial natural increase in the concentration of essential minerals. Potassium accumulated significantly in MPF (0.97%) and MYF (0.53%), while calcium surged from 28.47% (control) to peaks of 68.67% (MPF) and 65.63% (MYF). Magnesium uniformly exceeded 81% across all test groups, alongside prominent accumulations of iron and zinc. However, phosphorus was significantly depressed in the cassava peel group (MCF: 9.37%), altering optimal dietary Ca/P ratios. Ultimately, replacing 50% of maize with root crop by-products offers a viable strategy for maintaining organic matter stability and enhancing mineral content, as long as targeted micronutrient balancing is applied for sustainable feed production.

Keywords: Circular economy; Agro-industrial waste; Alternative energy sources; Tuber peel meals; Mineral bioavailability; Feed formulation.

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1. INTRODUCTION

The dramatic increase in world population and the increase in industrialization necessitates the upsurge in industrial and agricultural activities throughout the world (Aruna *et al.,*2017). Consequent to these global demographic and economic shifts, the livestock sector-particularly poultry-has experienced rapid intensification, emerging as the fastest-growing agricultural sub-sector driven by an unprecedented demand for meat and eggs (Mottet & Tempio, 2017). Within this framework, poultry production serves as a critical pillar for food security and revenue generation in developing countries, providing high-quality, affordable animal protein to millions of households (Attia *et al.,*2022; Birhanu *et al.,*2023). However, this escalating global demand for poultry products has placed unprecedented pressure on conventional feed security, exposing the industry to high price volatility and a critical competition for arable land between human food and animal feed (Birhanu *et al.,*2023; Oosting *et al.,*2022). The economic pressures created by the high price volatility often led to feed accounting for up to 80% of total production costs, leaving small-scale farmers vulnerable to economic instability (ICAR, 2016; Attia *et al.,*2022). Concurrently, agro-industrial processing of root and tuber crops generates billions of tons of peel waste annually that are largely abandoned in landfills or disposed of indiscriminately, contributing heavily to greenhouse gas emissions and environmental degradation (Nath *et al.,*2023). Valorizing these specific agricultural wastes into poultry feed matrices offers a strategic, dual-purpose solution that advances a circular bioeconomy while driving down production costs (Nath *et al.,* 2023; Yafetto *et al.,* 2023). Tuberous crop residues, specifically cassava peels, yam peels, and potato peels, represent a massive reservoir of underutilized nutrients including carbohydrates, minerals, and essential vitamins (Enenebeaku *et al.,* 2018; Jumare *et al.,* 2024). By channeling these specific by-products into animal feed, producers can significantly reduce production costs while mitigating the environmental impacts of waste disposal (Onu-Okpara *et al.,* 2019; Yafetto *et al.,* 2023). Agricultural wastes are rich reservoirs of essential nutrients; for instance, materials like pineapple peels, watermelon peels, and cassava bagasse have been found to contain significant levels of vitamins A, D, E, and B_{12}, which are crucial for bird growth, immune health, and egg production (Enenebeaku *et al.,* 2018). Despite this potential, many agricultural by-products are limited by high fiber content, low protein profiles, and the presence of anti-nutritional factors (ANFs) such as cyanide in cassava (Jumare *et al.,* 2024; Yafetto *et al.,* 2023). To overcome these barriers, advanced bioprocessing techniques like probiotic fortification (e.g., using *Lactobacillus fermentum*) and microbial fermentation are employed to enhance nutrient digestibility, increase weight gain, and reduce the presence of pathogens like *Eschericia coli* (Onu-Okpara *et al.,* 2019; Yafetto *et al.,* 2023). Furthermore, the utilization of agricultural and household waste material within small-scale poultry production serves as an engine for nutritional security and social empowerment, given that rural farmwomen are typically the primary custodians and managers of these flocks (Singh *et al.,* 2022). Therefore, providing access to income-generating technologies that utilize household leftovers and agricultural by-products strengthens the economic resilience of smallholders and promotes gender balance in rural communities (Birhanu *et al.,* 2023; Dash, 2015). Ultimately, integrating agricultural wastes into poultry feed formulation fosters a more sustainable, economical, and environmentally friendly production system that supports global food security (Attia *et al.,* 2022; Nath *et al.,* 2023). To address the challenges of food-feed competition and the accumulation of agro-industrial waste, this study aimed to evaluate the nutritional effectiveness and production viability of substituting conventional energy sources with root and tuber peel wastes in poultry diets. By exploring these formulations, this research aims to provide an empirical framework for the practical integration of non-conventional agro-wastes into sustainable, cost-effective poultry feed matrices.

2. MATERIALS AND METHODS

2.1 Procurement of Feed Ingredients and Agro-Wastes

Fresh agricultural waste products, comprising potato (*Solanum tuberosum*), yam (*Dioscorea* species), and cassava (*Manihot esculenta*) peels, were obtained from local domestic and commercial culinary processing hubs in Afikpo, Ebonyi State, Nigeria. Core conventional ingredients used for feed compoundment, including yellow maize, soybean meal, palm kernel cake (PKC), spent grains, oyster shell, bone meal, fish meal, iodized salt, and vitamin-mineral premixes, were purchased from Rare-Bond Limited (Afikpo, Nigeria).

2.2. Processing and Anti-Nutritional Factor (ANF) Mitigation

To optimize nutrient bio-availability and suppress endogenous anti-nutritional factors (such as cyanogenic glycosides in cassava, tannins in yam, and glycoalkaloids in potato) that limit monogastric performance, an improved multi-stage hydrothermal processing protocol was adopted according to methodologies validated previously by Oyeleke *et al.,* (2012). The raw root and tuber peels were thoroughly washed to clear extraneous debris, chopped, submerged in fresh water for an anaerobic soaking period of 24 hours, parboiled at 80°C for 10 minutes, and subsequently sun-dried in an open-air until moisture levels were below 12%. Dried samples were milled to a fine mash using a commercial hammer mill to achieve a consistent particle index for formulation.

2.3 Experimental Diets and Feed Formulation

The composition matrix of the diets was designed following the foundational nutrition principles outlined by Oyenuga (1985). The key experimental macro-ingredients and micro-supplements were pulverized, proportioned, and mechanically blended to guarantee absolute homogeneity across four iso-nitrogenous and iso-energetic dietary regimes as outlined in Table 1:

- MFF: Control diet containing 100% conventional maize-formulated feed.
- MPF: Experimental diet containing a 50%:50% ratio of maize and potato peel meal.
- MYF: Experimental diet containing a 50%:50% ratio of maize and yam peel meal.
- MCF: Experimental diet containing a 50%:50% ratio of maize and cassava peel meal.

Table 1: Formulation of Poultry Feed (Layers Mash)

Component	MFF	MPF	MYF	MCF
Maize (g)	500	250	250	250
Yam peel (g)	0	250	0	0
Cassava peel (g)	0	0	250	0
Potato peel (g)	0	0	0	250
Soya meal (g)	125	125	125	125

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Component	MFF	MPF	MYF	MCF
Methionine (g)	4	4	4	4
Lysine (g)	4	4	4	4
Palm kernel cake (g)	50	50	50	50
Oyster (g)	20	20	20	20
Bone meal (g)	20	20	20	20
Fish meal (g)	20	20	20	20
Salt (g)	3	3	3	3
Wheat bran (g)	125	125	125	125
*Premix (g)	2.5	2.5	2.5	2.5

**Premix supplied per kg of feed: Vit. A 10,000 iu, Vit. D3 2000 iu, Vit. E 5 iu, Vit. K 2mg, Riboflavin 4.20mg, Vit. B_{12} 0.01mg, Panthothenic acid 5mg, Micotic acid 20mg, Folic acid 0.5mg, Chlorine 3mg, Mg 55mg, Fe 20mg, Cu 10mg, Zn 50mg, Co 125mg, & Iodine 0.8mg.*

2.4. Proximate and Mineral Quantification (Feed Analyses)

The macro-nutritional, elemental, and structural mineral profiles of the four formulated feeds were determined in triplicate using standardized analytical regimens.

Proximate Analyses: Moisture content (MC), Dry matter (DM), crude protein (CP), ether extract (EE), crude fiber (CF), total ash content (TA), and organic matter (OM) fractions were assayed in conformity with the official protocols of the Association of Official Analytical Chemists (AOAC, 1990), alongside validation techniques detailed by Pearson (1976).

Carbohydrate & Energy Metrics: The nitrogen-free extract (NFE, %) was calculated mathematically by difference on a dry-matter basis using the following equation:

$$NFE\ (\%) = 100 - (\%\,CP + \%\,\mathrm{EE} + \%\,\mathrm{CF} + \%Ash + \%\,MC) \quad (1)$$

Total metabolizable energy (ME) of the samples were estimated from the proximate composition data using the Modified Carpenter and Clegg equation.

$$ME\ (kcal/kg) = 53 + (38\ x\ \%CP) + (85.5\ x\ \%EE) + (41.8\ x\ \%NFE) \quad (2)$$

The energy values were further converted to megajoules per kilogram (MJ/kg) using the conversion factor:

$$ME\ (MJ/kg) = \frac{ME\ (kcal/kg)}{239.006} \quad (3)$$

The metabolizable energy was reported as kcal/kg and MJ/kg of sample.

Mineral and Trace element Profiling:

Sodium (Na^+) and potassium (K^+) concentrations were analyzed with a flame photometer. Total phosphorus content was estimated using the standard Vanado-molybdate colorimetric method. The concentrations of other macro and micro mineral elements – calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn) were quantified using atomic absorption spectrophotometer (Buck Scientific, 210 VG) under optimized element-specific hollow-cathode lamp wavelengths.

Nutritional Mineral Ratios:

To evaluate the physiological balance and potential bio-availability interactions of the feed matrices, the structural mineral relationships were mathematically calculated as follow-up proportional indices:

$$Sodium - to - Potassium\ Ratio = \frac{Na}{K} \quad (1)$$

$$Zinc - to - Copper\ Ratio = \frac{Zn}{Cu} \quad (2)$$

$$Calcium - to - Phosphorous\ Ratio = \frac{Ca}{P} \quad (3)$$

2.5 Statistical Analysis

All laboratory determinations were executed in triplicate (n=3). The data generated were subjected to descriptive statistical analysis using SPSS Version 26.0. Quantitative values were expressed as the Mean ± Standard Deviation. Means were separated and evaluated using analysis of variance (ANOVA), with statistical significance defined at $P < 0.05$.

3. RESULTS AND DISCUSSIONS

3.1. Proximate Composition of Experimental Rations

The results of the proximate evaluation of the control diet (MFF) and the root/tuber peel-substituted diets (MPF, MYF, and MCF) presented in Table 2 revealed statistically significant differences ($p < 0.05$) across all evaluated nutritional metrics.

Table 2: Proximate Compositions of the Formulated Poultry Feeds

Proximate	MFF	MPF	MYF	MCF
Crude Protein (%)	13.78±0.10^c	19.83±0.08^a	18.78±0.07^b	13.05±0.05^d
Ether Extract (%)	4.50±0.40^a	4.40±0.30^a	3.70±0.10^b	3.80±0.10^b
Crude Fibre (%)	13.90±0.30^d	15.70±0.50^b	14.90±0.01^c	17.80±0.04^a
Ash Content (%)	9.60±0.00^a	8.60±0.20^c	9.70±0.20^a	9.30±0.10^b

Proximate	MFF	MPF	MYF	MCF
Organic Matter	90.40±0.00[c]	91.40±0.20[a]	90.30±0.20[c]	90.70±0.10[b]
Moisture Content	15.30±0.10[b]	16.00±0.60[b]	14.30±0.40[c]	18.00±0.30[a]
Dry Matter (%)	84.70±0.10[b]	84.00±0.60[b]	85.70±0.40[a]	82.00±0.30[c]
Nitrogen Free Extract (%)	47.42±0.89[a]	35.47±2.94[c]	38.92±0.82[b]	38.05±0.05[bc]
Metabolizable Energy (MJ/kg)	10.43	9.50	9.62	8.72

Values are expressed as mean ± standard deviation (n = 3). Means within the same row carrying different superscript letters are significantly ($p < 0.05$) different from each other.

Crude Protein and Ether Extract

The results showed that the crude protein content varied significantly among treatments ($p < 0.05$), ranging from 13.05 % in MCF to a peak of 19.83 % in MPF. Interestingly, substituting 50% of the maize with potato peels (MPF, 19.83 %) and yam peels (MYF, 18.78 %) resulted in a notable increase in total dietary protein compared to the baseline MFF control (13.78 %). This enrichment is attributable to the presence of non-protein nitrogenous compounds and functional storage proteins inherent to *Solanum tuberosum* and *Dioscorea* cortex matrices. Conversely, the significant drop observed in the cassava peel diet (MCF) reflects the notoriously low protein density characteristic of unfermented *Manihot esculenta* byproducts. The elevated CP values recorded in the potato peel (MPF) and yam peel (MYF) rations align with the findings of Yohannes *et al.,* (2024), who demonstrated that dried potato peel yields a CP value of 8.4%, and Aguihe *et al.,* (2021), who observed that dried yam peel contains 10.52% CP. Conversely, the low CP values observed in the cassava peel ration (MCF) align with 2.1% CP values observed by Gunun *et al.,* (2023) showing that unfermented cassava peel is a poor source of nitrogenous compounds.

Regarding the lipid profile, the ether extract (EE) values were statistically comparable and highest between MFF (4.50 %) and MPF (4.40 %), but dropped significantly ($p < 0.05$) in MYF (3.70 %) and MCF (3.80 %). This drop aligns with the inherently low baseline lipid content of these root residues, as raw cassava peels typically exhibit an EE range of 0.0% to 3.3% (Oloruntola *et al.,*2016; Nsa *et al.,*2022), while dried white yam peels yield baseline EE values as low as 1.11% to 2.28% (Aguihe *et al.,*2021; Ukanwoko, 2020). This transition implies a clear dilution of dense lipid compounds when shifting to yam and cassava alternatives, which must be carefully monitored to avoid hindering micelle formation and subsequent fat-soluble vitamin absorption in monogastric animals.

Fiber and Carbohydrate Dynamics

The crude fiber (CF) content increased sequentially from the baseline MFF (13.90 %), MPF (15.70%), MYF (14.90 %) up to a maximum value in MCF (17.80 %) ($p < 0.05$). The observed trend is due to the progressive accumulation of structural non-starch polysaccharides (cellulose, hemicellulose, and lignin) in the root peel waste. Although, elevated fiber levels can restrict upper gut passage rates in young chicks (Mateos *et al.,*2012), the observed values in MPF and MYF fall within tolerable limits for developing or adult flocks. The findings of this study mirror several previous studies: the MYF CF values support the 13.25% reported by Aguihe *et al.,* (2021); the MCF values (15.18%) parallel the data from Nsa *et al.,* (2023); and the MPF values (2.5%) agree with the trends observed by Javed *et al.,* (2019).

Mineral Ash, Organic Matter, Dry Matter, and Moisture Profiles

The result showed that the total inorganic ash varied considerably based on the unique mineral capacities of the tuber peels. Total ash peaked in the yam peel ration (MYF: 9.70 %) and the maize control (MFF: 9.60 %), while dropping significantly in the potato variant (MPF: 8.60 %) ($p < 0.05$). The superior mineral retention observed in the MYF ration strongly corroborates the findings of Aguihe *et al.,* (2021), who reported that processed yam peel meals (*Dioscorea rotundata*) are robust sources of structural ash (8.15%) capable of maintaining or elevating dietary mineral balances when substituting cereal fractions. Conversely, the significant decline ($p < 0.05$) in ash within the MPF group matches the trends outlined by Javed *et al.,* (2019) and Nsa *et al.,* (2023), who noted that potato peel periderms inherently contain a lower, more volatile concentration of inorganic minerals compared to yam tubers. This variation suggests that while both tuber peels can serve as alternative energy feedstock, yam peel substitutions provide a more stable macro-mineral profile, minimizing the drop in total inorganic ash relative to standard commercial controls.

The organic matter (OM) content of the formulated diets varied significantly ($p < 0.05$) among treatments, ranging from 90.30% in the yam peel-based diet (MYF) to 91.40% in the potato peel-based diet (MPF). This showcases a strong overall organic fraction despite the high inclusion level of alternative root and tuber wastes. These results align with those observed by Aguihe *et al.,* (2022), who demonstrated that the partial replacement of dietary maize with processed tropical root and tuber by-products preserves a high baseline of total organic matter (exceeding 90%) due to the inherently rich carbohydrate and organic matrix retained within root epicarps. However, the result of this study contrasts with that observed by Ukanwoko (2020), who reported substantially lower organic matter values in raw crop residues due to volatile shifts in structural total ash, which reached as high as 10.64% in specific local tuber varieties. This variance suggests that compounding these wastes at a strictly regulated 50% ratio stabilizes the total dietary organic load, making treatments like MPF highly effective at preserving critical nutrient density.

The moisture content observed in this study varied, with a minimum of 14.30% in the yam peel matrix (MYF) and reaching a maximum of 18.00% in the cassava-blended ration (MCF). The higher moisture capacity observed in the cassava-blended ration (MCF) accounts for its lower dry matter index (82.00%, $p < 0.05$) compared to all other treatment matrices. This hydro-retentive phenomenon in the cassava composite aligns with the findings of Oladimeji *et al.,* (2022), who noted that the porous starch network of unfermented cassava components acts as a water sink, naturally resisting rapid dehydration during standard drying and blending. Managing high-moisture ceiling is crucial during storage to prevent mold development and protect overall feed quality. Because commercial storage baselines typically dictate a maximum safe moisture cap of 12-13% to suppress fungal activity, the 18.00% threshold recorded in the MCF formulation presents a potential shelf-life risk that necessitates intentional post-formulation drying or pelletizing treatments to prevent mycotoxin contamination.

The results showed that the dry matter (DM) content of the formulated diets varied significantly ($p < 0.05$) among the treatment groups, ranging from 82.00% in MCF to 85.70% in MYF. These results are consistent with those reported by Gbenge *et al.,* (2021). Their research on tuber waste composite meals revealed that processed root and tuber residues consistently demonstrate a unique moisture-holding matrix. This matrix typically confines the final dietary dry matter to a range of 85% to 89% after the drying process. The sharp decrease in DM noted in MCF reflects an elevated core moisture content (18.00%), highlighting the strong water-binding and hygroscopic properties of cassava outer peel wall. Conversely, the results of this study contrast with those observed by Kpanja *et al.,* (2019), who reported a much more uniform and tightly preserved dry matter retention (90.03%) across intensive solar dehydration treatments of Irish potato residues. These comparative dynamics demonstrate that while a 50% replacement of conventional maize introduces clear physical variations based on the source tuber's structural fiber network, both the MPF and MYF configurations safely meet the physiological dry matter thresholds required for standard livestock feeding regimes.

Energetic Evaluations of the Feed Matrices

The results in Table 2 reveal distinct variations in both carbohydrate concentrations and energetic profiles, demonstrating a synchronized hierarchical pattern where MFF > MYF > MPF > MCF for both parameters. The NFE fraction, which represents soluble, non-structural carbohydrates such as starches and sugars, acted as the primary driver for these thermodynamic variances. Sample MFF exhibited the highest NFE content (47.42%), followed closely by MYF (38.92%) and MCF (38.05%), while MPF recorded the lowest carbohydrate density (35.47%). These results align with those observed by Nsa *et al.,* (2023), who demonstrated that substituting standard grain products with increasing amounts of cassava peel meal (CPM) induces a distinct reduction in total digestible carbohydrates due to the significant structural fiber dilution found within unrefined agricultural epicarp wastes. The result also aligns with those observed by Omole *et al.,* (2015), whose comparative evaluation of alternative root crop components showed that a 50% replacement level of conventional cereal matrices with raw tuber waste results in a systematic reduction of the soluble starch fraction calculated by difference. Conversely, the result of this study contrasts with that observed by Amaza (2021), who reported a remarkably high baseline nitrogen-free extract value of 66.56% for a sweet cassava variety grown in North-Eastern Nigeria. This indicates that the sharper decline to 38.05% observed in the cassava peel treatment (MCF) of this investigation stems from a higher dilution of non-starch polysaccharides or crude fiber within this specific raw processing pool. Furthermore, these results contrast with those observed by Kpanja and Kotso (2023), who discovered that unadulterated Irish potato peel meal could retain a dense, high-standing carbohydrate fraction with an NFE of up to 87.16%.

The calculated metabolizable energy (ME) of the diets closely mirrored the trends observed in the NFE results, highlighting the primary role that soluble carbohydrates play in dictating the caloric density of livestock feed. The control diet (MFF) possessed the highest energy concentration at 10.43 MJ/kg. Consistent with the contraction of the NFE fractions, the integration of root and tuber wastes reduced the calculated ME values to 9.62 MJ/kg for MYF, 9.5 MJ/kg for MPF, and 8.72 MJ/kg for MCF. This showed that replacing starch-dense, highly digestible maize with raw agro-industrial peels lowers metabolizable energy. This occurs because the increased crude fiber dilutes the feed's overall energy density, and potentially accelerates transit time through the digestive tract, ultimately reducing nutrient digestibility. This effect is most pronounced in the cassava peel diet (MCF), where the lowest ME (8.72 MJ/kg) directly coincides with the highest crude fiber (17.80%) and highest moisture content (18.00%). Nevertheless, the energy profiles of the yam (MYF) and potato (MPF) diets remained reasonably stable, hovering around 9.5–9.6 MJ/kg. This indicates that while a 50% replacement level alters the optimal energy base, these specific by-products still retain sufficient nutrient density to serve as viable, cost-effective alternative energy sources in formulated rations. The 8.72 MJ/kg metabolizable energy obtained in the cassava peel-substituted diet (MCF) contrasts with those observed by Amaza (2021), who obtained an estimated 2717.96 kcal/kg (approximately 11.37 MJ/kg) metabolizable energy in raw sweet cassava peel. Conversely, these results align with those observed by Salami (2000), who demonstrated that substituting maize with raw, unfermented agro-industrial tuber wastes like cassava and yam peels systematically depresses the metabolizable energy profiles of the complete feed due to a simultaneous expansion of the indigestible crude fiber fraction which acts as a physical energy diluent. These findings demonstrate that while partial root crop substitutions offer a viable route for agricultural waste valorization, the accompanying reduction in metabolizable energy across all experimental groups (ranging from 8.72 to 9.62 MJ/kg compared to 10.43 MJ/kg in the control) necessitates careful macro-nutrient balancing to satisfy the energetic requirements of livestock.

Mineral Composition of Experimental Rations

The mineral composition of the formulated diets, as shown in Table 3, indicates significant changes ($p < 0.05$) in both macro and micro-mineral elements following the 50% substitution of conventional maize with different root and tuber peel meals. The result showed that Potassium (K) concentrations were significantly elevated in the potato peel-based diet (MPF: 0.97%) and the yam peel-based diet (MYF: 0.53%) compared to the control diet (MFF: 0.24%). This trend aligns with observations by Vaitkevičienė (2019), who confirmed that potassium represents the most prominent mineral deposited within the peripheral tissues and outer epicarps of tuberous crops. Conversely, the cassava peel-based ration (MCF) yielded a baseline potassium concentration (0.22%) which is statistically comparable to the maize control. Sodium (Na) values stayed consistently stable across all treatments, ranging from 2.24% to 2.31%. This suggests that incorporating agro-industrial tuber wastes does not lead to a significant change in the dietary sodium content. Consequently, the calculated Na/K ratio dropped sharply from 9.33 in MFF down to 2.36 in MPF and 4.35 in MYF, a reduction driven primarily by the high potassium load of the alternative ingredients. For a better nutrient assimilation, the sodium-to-potassium ratios in the diets should be low (Ajala *et al.,*2020). The values obtained in this study were within the acceptable limits for livestock.

Calcium is known as a primary element for strong bone formation which helps animals to be healthy. It is also necessary in enzymes activation (Obasi *et al.,*2022). Calcium (Ca) and magnesium (Mg) profiles showed substantial accumulation in the peel-substituted diets. Calcium concentration increased drastically from 28.47% in the maize control to 68.67% in MPF and 65.63% in MYF, while the cassava peel diet (MCF) experienced a more modest, non-significant increase (30.35%). This profound enhancement in MPF and MYF implies that potato and yam peel fractions serve as exceptionally rich repositories of structural calcium, reflecting the intense mineral deposition that occurs at the soil-root interface. This observation aligns with reports by Omole *et al.,* (2015), where the incorporation of unrefined root crop epicarp wastes systematically fortified the calcium matrix of formulated feeds. Magnesium levels also rose uniformly from 64.23% in the control to values exceeding 81% across the three test groups (MPF, MYF, and MCF). This uniform increase across the substituted rations aligns with the findings of Amaza (2021), who demonstrated that tropical tuber wastes like cassava peel profiles contain highly concentrated baseline magnesium fractions, thereby offering a viable means of natural dietary magnesium fortification.

Table 3: Mineral Elements of the Formulated Feeds (mg/kg)

Mineral Element	MFF	MPF	MYF	MCF
Potassium (K)	0.24±0.02[a]	0.97±0.03[b]	0.53±0.02[c]	0.22±0.02[a]
Sodium (Na)	2.24±1.06[a]	2.29±0.02[a]	2.31±0.09[a]	2.31±0.26[a]
Calcium (Ca)	28.47±1.19[c]	68.67±0.58[a]	65.63±0.42[b]	30.35±2.00[c]
Magnesium (Mg)	64.23±0.75[b]	81.33±1.53[a]	83.37±0.81[a]	83.60±1.85[a]
Phosphorous (P)	11.32±0.67[c]	17.65±1.14[a]	14.48±0.71[b]	9.37±0.09[d]
Iron (Fe)	0.84±0.08[d]	1.41±0.02[b]	2.13±0.03[a]	1.14±0.02[c]
Zinc (Zn)	0.003±0.00[d]	0.62±0.02[a]	0.28±0.02[b]	0.07±0.01[c]
Copper (Cu)	1.32±0.10[a]	0.48±0.02[b]	0.57±0.03[b]	0.50±0.01[b]
Manganese (Mn)	0.14±0.02[a]	0.07±0.02[b]	0.02±0.01[c]	0.08±0.02[b]
Na/K	9.33	2.36	4.35	10.5
Zn/Cu	0.02	1.29	0.49	0.14
Ca/P	2.51	3.89	4.53	3.24

Values are expressed as mean ± standard deviation (n = 3). Means within the same row carrying different superscript letters are significantly ($p < 0.05$) different from each other.

Phosphorus (P) dynamics displayed divergent trends depending on the specific root crop substitute. While phosphorus significantly accumulated in the potato peel feed (MPF: 17.65%) and yam peel feed (MYF: 14.48%) compared to the control (11.32%), it was significantly depressed in the cassava peel treatment (MCF: 9.37%). This variation caused the dietary Ca/P ratios to stretch from 2.51 in MFF to 3.89 in MPF and 4.53 in MYF. The wider proportion requires careful consideration during feed formulation to prevent imbalances that could hinder optimal bone calcification.

The observed depletion of phosphorus in MCF highlights a notable limitation found in various raw cassava peel residues. This finding aligns with the nutritional evaluations conducted by Nsa *et al.,* (2023), who indicated that alternative cassava byproduct rations often necessitate inorganic phosphorus supplementation to address the natural mineral depletion present in the root skin. Trace mineral profiles were also altered by the inclusion of the tuber by-products. Iron is a micronutrient which is a component of many enzymes that are required in metabolism and helps in red blood cells formation (Obasi *et al.,*2022). In this study, iron content increased significantly from 0.84% in the control to 1.14% in MCF, 1.41% in MPF, and reached a peak of 2.13% in MYF. Zinc (Zn) content followed a similar pattern, expanding from a negligible level in the pure maize feed (0.003%) to 0.07% in MCF, 0.28% in MYF, and a maximum of 0.62 % in MPF. The increases in iron and zinc levels correspond with the findings of Aguihe *et al.,* (2022), who evaluated alternative tuber meals. Their research highlighted that unrefined processing by-products from root skins serve as concentrated sources of key soil-derived trace metals, especially when compared to highly processed or polished grain alternatives. Conversely, levels of copper (Cu) and manganese (Mn) were significantly higher in the conventional maize control group than in the alternative test formulations. This discrepancy suggests that while root crop wastes effectively supply iron, zinc, calcium, and magnesium, they are less efficient in providing copper and manganese. As a result, targeted premix adjustments may be necessary in precision livestock feeding programs.

4. CONCLUSION

This study shows that by-products from agro-industrial processing of roots and tubers - specifically, meals made from potato, yam, and cassava peels- can effectively replace 50% of conventional maize in livestock diets without compromising the integrity of the organic matter in the feed matrix. While the structural fiber inherent to these outer epicarps naturally induces a linear reduction in nitrogen-free extract (NFE) fractions and subsequently depresses the calculated metabolizable energy (ME) profiles—most notably within the cassava peel-based diet (MCF)—the alternative formulations maintain sufficient nutrient density to serve as viable caloric bases. Furthermore, the dietary integration of these tuber wastes provides a profound, natural fortification of essential macro and trace minerals, yielding significant accumulations of potassium, calcium, magnesium, iron, and zinc across the test groups compared to a pristine maize baseline. However, the accompanying widening of the dietary Ca/P and Zn/Cu ratios emphasizes the need for targeted micronutrient adjustments when formulating these diets. Ultimately, substituting conventional grains with underutilized root peels offers a physiologically viable, resource-efficient strategy for precision feed manufacturing, contributing directly to sustainable, circular-economy livestock production systems.

REFERENCES

- Aguihe, P. C., Kehinde, A. S., Halidu, S. K., Joshua, D. A., Samuel, K. U., Komolafe, P. L., & Ilaboya, I. I. (2021). Performance and egg qualities of laying japanese quails fed yam peel meal-based diets with enzymes complex+yeast supplementation. *Acta Scientiarum. Animal Sciences*, *44*(1), e53335. https://doi.org/10.4025/actascianimsci.v44i1.53335
- Ajala, L. O., Dafallaha, O. B, Obasi, N, A., Fasuan, T. O., & Ogundapo, S. S. (2020). Mineral compositions of infant complementary foods in relation to dietary daily intake and synergistic/antagonistic interrelationships. Intl. J. Food Sci. Nutr., 71(7), 804–814. https://doi.org/10.1080/09637486.2020.1738353
- Amaza, I. B. (2021). Determination of proximate composition, amino acids, minerals and phytochemical profile of Cassava (*Manihot esculenta*) peel from sweet cassava variety grown in Yobe State of North Eastern Nigeria. *Nigerian Journal of Animal Production*, 48(1), 124–134. https://doi.org/10.5555/20210355764.
- Aruna, T. E., Aworh, O. C., Raji, A. O., & Olagunju, A. I. (2017). Protein enrichment of yam peels by fermentation with *Saccharomyces cerevisiae* (BY4743), *Ann. Agric. Sci.* 62: 33–37.
- Association of Official Analytical Chemists. (1990). *Official methods of analysis* (15th ed.). Association of Official Analytical Chemists.
- Attia, Y. A., Rahman, M. T., Hossain, M. J., Basiouni, S., Khafaga, A. F., Shehata, A. A., & Hafez, H. M. (2022). Poultry production and sustainability in developing countries under the COVID-19 crisis: Lessons learned. *Animals*, 12(5), 644. https://doi.org/10.3390/ani12050644
- Birhanu, M. Y., Osei-Amponsah, R., Obese, F. Y., & Dessie, T. (2023). Smallholder poultry production in the context of increasing global food prices: Roles in poverty reduction and food security. *Animal Frontiers*, *13*(1), 17–27. https://doi.org/10.1093/af/vfac069
- Dei, H. K. (2017). Assessment of maize (*Zea mays*) as feed resource for poultry. *Poultry Science*, 1–12. https://doi.org/10.5772/65363.
- Enenebeaku, C. K., Enenebeaku, U. E., & Ezejiofor, T. I. N. (2018). Evaluation of selected agricultural wastes as viable sources of vitamin supplements in poultry feeds. *World News of Natural Sciences*, *20*, 103–120.
- Gbenge, A. A., Oluremi, O. I. A., & Nwosu, C. O. (2021). Proximate composition, haematology, carcass characteristics and meat yield of growing rabbits fed yam-cassava peel composite meal. *Nigerian Journal of Animal Production*, *48*(4), 115–124.

- Gunun, P., Cherdthong, A., Khejornsart, P., Wanapat, M., Polyorach, S., Kaewwongsa, W., Gunun, N. (2023). Replacing Concentrate with Yeast- or EM-Fermented Cassava Peel (YFCP or EMFCP): Effects on the Feed Intake, Feed Digestibility, Rumen Fermentation, and Growth Performance of Goats. *Animals*, 13, 551. https://doi.org/10.3390/ani13040551.
- ICAR-Central Institute for Women in Agriculture. (2016). *Empowering farmwomen through livestock and poultry intervention* (Compendium: ICAR Sponsored Short Course).
- Javed, A., Ahmad, A., Tahir, A., Shabbir, U., Nouman, M., & Hameed, A. (2019). Potato peel waste—its nutraceutical, industrial and biotechnological applications. *AIMS Agriculture and Food*, *4*(3), 807–823. https://doi.org/10.3934/agrfood.2019.3.807.
- Jumare, F. I., Salleh, M. M., Ihsan, N., & Hussin, H. (2024). Cassava waste as an animal feed treatment: past and future. *Reviews in Environmental Science and Bio/Technology*, *23*, 839–868. https://doi.org/10.1007/s11157-024-09701-7.
- Kpanja, E. J., Duru, S., Omage, J. J., Sekoni, A. A., & Gonjoh, A. (2019). Proximate composition, anti–nutritional factors and the effect of Irish potato (*Solanum tuberosum* L.) peels on the performance and carcass characteristics of broiler chickens. *Nigerian J. Anim. Sci,* 21 (2): 214-222.
- Kpanja, E. J., & Kotso, A. A. (2023). Proximate composition and anti–nutritional factors of Irish potato (*Solanum tuberosum* L.) peel meal and its effect on the performance and carcass characteristics of weaner rabbits. *FUDMA Journal of Agriculture and Agricultural Technology*, *9*(4), 108–113. https://doi.org/10.33003/jaat.2023.0904.15.
- Mateos, G. G., Jiménez-Moreno, E., Serrano, M. P., & Lázaro, R. P. (2012). Poultry response to high levels of dietary fiber sources varying in physical and chemical characteristics. *Journal of Applied Poultry Research*, *21*(1), 156-174. https://doi.org/10.3382/japr.2011-00477.
- Mottet, A., & Tempio, G. (2017). Global poultry production: current state and future outlook and challenges. *World's Poultry Science Journal*, *73*(2), 245–256. https://doi.org/10.1017/s0043933917000071.
- Nath, P. C., Ojha, A., Debnath, S., Sharma, M., Nayak, P. K., Sridhar, K., & Inbaraj, B. S. (2023). Valorization of food waste as animal feed: A step towards sustainable food waste management and circular bioeconomy. *Animals*, *13*(8), 1366. https://doi.org/10.3390/ani13081366
- Nsa, E. E., Ozung, P. O., Extuk, E. A., & Archibong, E. E. (2023). Economics and effect of replacing wheat offal with cassava peel meal on growth performance, nutrient digestibility of growing pigs. *African Journal of Food, Agriculture, Nutrition and Development*, 23(23540), 24423-24442. https://doi.org/10.18697/ajfand.123.23540.
- Obasi, N. A., Obasi S. E., Ajala L. O., Aloh G. O., Aloke C., Ogundapo S. S. And Onyeji G. N. (2022). Nutrient interaction and health risk assessment of cereal grains on Nigerian's markets. Journal of Food Quality and Hazards Control. 9, 137–146. https://doi.org/10.18502/jfqhc.9.3.11152
- Oladimeji, S. O., Adebayo, A. B., Okike, I., & Blümmel, M. (2022). Nutritional composition of cassava (*Manihot esculenta* Crantz) peel products. *Livestock Research for Rural Development*, 34(10), 1–7.
- Oloruntola, O., Agbede, J., Onibi, G., & Igbasan, F. (2016). Replacement value of rumen liquor fermented cassava peels for maize in growing rabbit diet. *Archivos de Zootecnia*, 65(249), 89-97. https://doi.org/10.21071/az.v65i249.446.
- Omole, A. J., Popoola, Y. A., & Raji, A. M. (2015). Effect of dietary replacement of maize with yam and Irish potato peel meals on the growth and economic performance of growing rabbits. *Nigerian Journal of Animal Production*, 42(1), 94–101.
- Onu-Okpara, I. Q., Oranusi, S., & Okagbue, H. (2019). Production of probiotic-fortified composite animal feed from food and agricultural waste material. *J Adv Vet Anim Res*. 6(4):544–548.
- Oosting, S., van der Lee, J., Verdegem, M., de Vries, M., Vernooij, A., Bonilla-Cedrez, C., & Kabir, K. (2022). Farmed animal production in tropical circular food systems. *Food Security*, *14*(1), 273–292. https://doi.org/10.1007/s12571-021-01205-4
- Oyeleke, S. B., Dauda, B. E. N., Okoliegbe, I. N., & Ojebode, T. (2012). Production of bioethanol from cassava and sweet potato peels. *Advances in Environmental Biology*, *6*(1), 241–245.
- Oyenuga, V. A. (1985). *Nigeria's foods and feeding-stuffs: Their chemistry and nutritive value*. Ibadan University Press.
- Pearson, D. (1976). *The chemical analysis of foods* (7th ed.). Churchill Livingstone.
- Salami, R. I. (2000). Dietary replacement of processed cassava peel-leaf blends for maize in livestock nutrition. *Journal of Agricultural Sciences*, 45(2), 112–120.
- Singh, M., Mollier, R. T., Paton, R. N., Pongener, N., Yadav, R., Singh, V., Katiyar, R., Kumar, R., Sonia, C., Bhatt, M., Babu, S., Rajkhowa, D. J., & Mishra, V. K. (2022). Backyard poultry farming with improved germplasm: Sustainable food production and nutritional security in fragile ecosystem. *Frontiers in Sustainable Food Systems*, *6*, Article 962268. https://doi.org/10.3389/fsufs.2022.962268.
- Ukanwoko, A. I. (2020). Varietal Variation in the Nutritive Value of Some Crop Residues Fed to Small Ruminants. *International Journal of Agricultural Bioscience*, *9*(2), 70-73.

- Vaitkevičienė, N. (2019). A comparative study on proximate and mineral composition of coloured potato peel and flesh. *Journal of the Science of Food and Agriculture*, 99(11), 5111–5119.
- Yafetto, L., Odamtten, G. T., & Wiafe-Kwagyan, M. (2023). Valorization of agro-industrial wastes into animal feed through microbial fermentation: A review of the global and Ghanaian case. *Heliyon*, *9*(3), e14814. https://doi.org/10.1016/j.heliyon.2023.e14814
- Yohannes, M., Kechero, Y., & Tadele, Y. (2024). Nutritional and Phytochemical Characteristics of Fruits and Vegetable Wastes as Livestock Feed: A Case Study in Gamo Zone, Southern Ethiopia. *Veterinary Medicine International*, Article 4427876. https://doi.org/10.1155/2024/4427876Digital Object Identifier (DOI).