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Emerging Use of Nonconventional Feed Resources in Rabbit Nutrition: Functional Properties, Sustainability and the Implications on Meat Quality: A Review

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Abstract

Conventional feed resources like maize and wheat are still under demand due to the growing demand for animal protein worldwide, especially in countries that are developing. Feed expenses continue to be a major obstacle in the production of rabbits, an important source of cheap, lean protein. Agro-industrial by-products such dried watermelon rinds, cassava peels, citrus pulp, palm kernel cake, and brewer's grains are examples of non-conventional feed resources (NCFRs) that are being researched more and more as substitutes. These residues, which are frequently thrown away as waste, still contain nutrients and bioactive substances that can improve meat quality, development, and carcass performance while reducing environmental impacts.

This review addresses the effects of NCFRs on the functional properties (antioxidant status, lipid oxidation, fatty acid composition), sensory qualities, and physical and chemical traits (tenderness, cooking loss, color stability, and water-holding capacity) of rabbit meat. Research, such as trials using dried watermelon rind, shows that adding NCFRS to rabbit meat does not affect performance and may even increase its stability and consumer appeal. Sustainability implications are considered across environmental (waste reduction, circular economy), economic and social (lower feed costs, rural livelihoods), and food system (resource availability, protein diversification, resilience to climate shocks) dimensions. Notwithstanding these advantages, there are still gaps in customer acceptance, meat quality results, nutrient standardization, and life-cycle evaluations. Utilizing NCFRs in rabbit production presents chances to lower feed expenses, increase the value of agro-industrial waste, enhance the functionality of meat, and support sustainable livestock systems.

Keywords: Rabbit Nutrition, Non-Conventional Feed Resources (NCFRs), Agro-Industrial By-Products, Meat Quality, Functional Properties, Sustainability

1. Introduction

Livestock production in developing countries faces increasing pressure due to the growing demand for animal protein and the competition between humans and livestock for conventional feed resources (Makkar, 2018) [35]. In a developing nation like Nigeria, livestock animals are often fed with grains and cereals such as millet, rice, wheat, and most especially, maize which is also crucial in human diets (Teguia *et al*., 2004). This overlap has resulted in a persistent feed-food conflict, notably increasing the cost of feed and intensifying food insecurity. (Nicholas, 2023) [37]. Over the years, 60% of the maize produced globally has been consumed by livestock, particularly as a primary energy source (Klopfenstein *et al*., 2013). Amidst these challenges, research is increasingly directed towards non-conventional feed resources (NCFRs) and agro-industrial by-products as sustainable alternatives.

Non-conventional feed resources (NCFRs) are feed materials not traditionally used in livestock diets, often derived from agricultural residues or agro-industrial processing (Amata, 2014) [8]. These include leaf meals, fruit peels, oilseed cakes, brewers' grains, cassava peels, and citrus pulp, among others (Ben Salem *et al*., 2004; Chadhokar, 1984) [12, 14]. Although a significant number of these materials are low in nutrient density and may contain anti-nutritional factors, but they are frequently cheap, abundant, and not often utilized.

Chisoro *et al.,* (2023) [15] reported that the strategic usage of these materials especially when processed appropriately offers a promising soluton to alleviating feed shortages, reducing environmental waste, and improving the economics of livestock production. However, moisture content, perishability, seasonal availability, and the requirement for detoxifying processes must all be addressed before they can be used on a large basis.

Among such underutilized by-products is watermelon rind, a fibrous waste product of significant environmental concern in Nigeria. Nigeria is one of Africa's largest producers of watermelon, particularly in its northern regions (Bosede *et al*., 2012) [13]. It has a high concentration of minerals, carotenes, vitamin A, C, K, riboflavin, and citrulline which is converted into arginine that helps to improve blood flow, exercise performance and muscle recovery (Gwana *et al*., 2014). Otu *et al.,* (2021) reported that a substantial amount of this rind is one of the many unwanted by-products often tossed off carelessly as wastes into the environment, hereby polluting the environment. Processing the rind by drying and lowering its water content then turning into powder helps to extend shelf life and reduce microbial spoilage (Sewald and DeVries, 2015; Ho, 2016) [42, 28], making it a viable feed ingredient.

Rabbits (*Oryctolagus cuniculus*) are sensitive micro-livestock species (Diina, 2019) [21] that have been researched to be the most affordable means of producing animal protein (Ajala and Balogun, 2004) [6]. They also possess the ability to adapt to seasonal changes due to the amount of feed available (Aduku and Olukosi, 1990) [3] and offer a suitable platform for testing such alternative feed supplies because of their efficient feed conversion, short production cycles, and high reproduction rates. (FAO, 2019) [26]. Their ability to utilize fibrous plant material and adapt to a wide range of diets makes them eligible for different trials of NCFRS-based nutrition. Additionally, rabbit meat is lean, high in protein (20.8%), low in fat (1–3%), and contains essential micronutrients, making it appealing to health-conscious consumers (ARBA, 2023) [9].

Although several studies have investigated the impact of watermelon rind inclusion on the growth performance and carcass characteristics of livestock such as broiler chickens and albino rats (Okai *et al*., 2009 [38]; Otu *et al*., 2021), limited attention has been given to its effects in rabbits. This review explores the use of non-conventional feed resources (NCFRs) in rabbit nutrition, with a particular focus on how it influences meat quality, functional attributes, and environmental sustainability.

2. Rabbit Production

Cuniculture, the practice of growing rabbits for meat, originated from the Mediterranean and North American wherein agricultural traditions underwent industrialization in Europe in the 20th century, emphasizing improved carcass characteristics and production efficiency through breeding programs (Wikipedia, 2025) [45]. According to the global review conducted by Compassion in food business (2024), they reported that in 2021, around 570 million rabbits and hares were slaughtered globally, with China accounting for over half of total output (approximately 53%). Despite production development in areas of Asia, consumption trends have stagnated or dropped in several places. Global volume of rabbit meat fell from a peak of about 1.3 million tonnes in 2014 to about 832,000 tonnes in 2024, with anticipated modest growth Compound Annual Growth Rate, CAGR of about 0.2% through 2035.

The production of rabbits has benefits for the environment, because of its low greenhouse gas emissions, low land needs, and effective feed use, it has a comparatively tiny ecological influence and it is therefore in line with the objectives of sustainable food security (Siddiqui *et al.,* 2024) [43]. Their gestation period is approximately 30 days, they can produce more than one litter a year, and they have low initial investment, which makes them a good choice for smallholder systems in developing countries (Akinnusi *et al.,* 2007) [7].

Ajala and Balogun (2004) [6] reported that rabbit production was a convenient way of solving animal protein deficiency in developing countries. Rabbits are raised mainly for meat, skin and fur production, although they are also used as laboratory animals (Jiya *et al.,* 2013).

2.1 Rabbit Meat

Rabbit meat is regarded for its high-quality protein content (about 20-25% crude protein), which contains all essential amino acids with high biological value, including lysine and tryptophan especially in famous breeds like New Zealand White and California rabbits. The flesh is extremely lean, with fat levels ranging between 1-3%, and contains unsaturated fatty acids and low cholesterol content, making it a heart-healthy protein source. Rabbits are rich in critical micronutrients such B vitamins (B3, B6, B12), selenium, zinc, potassium, and phosphorus, making them a nutritious choice (Etukudo *et al.,* 2021).

In addition, it is known to be versatile, containing mild flavor and suitability for refrigeration and different methods of cooking (ARBA, 2023) [9]. It also offers excellent returns on investment. Rabbit meat is gradually gaining popularly due to its leanness, sustainability and nutritional worth (Adeyemi *et al.,* 2014) [2]. Every consumer's priority about meat are the physical qualities then the nutritional and chemical qualities which includes the colour, the texture, the taste and many more, depending on their preferences (Mayulu *et al.,* 2019; Akhigbe and Akaeze, 2023). The physical and chemical qualities of meat can be evaluated by paremeters such as; pH, cook loss, refrigeration loss, water absorptive power and water holding capacity (Umer *et al.,* 2021). Thesse parameters are crucial in determining the quality, yield and consumer satisfaction.

2.2 Rabbit Nutrition

Rabbits are small herbivores that exhibit selective feeding behaviors, prioritizing nutrient-dense plant components, such as tender shoots and leaves, over fibrous, older foliage. This behavior makes them concentrate selectors, a type of feeder that prefers high-energy foods. In the wild, this helps them take in food quickly while staying out of reach of predators (Joerg, 2024) [30]. Although their specific feed ingredients and proportions varies based on the age, the health of the rabbit and even the time of the year (AgriFarming, 2022) [4]. The use of concentrate feed by rabbit farmers has gained prevalence over the years, especially during dry seasons when there is little or no vegetation. This feed is an all-in-one pellet or nugget type to prevent selective feeding and supplies all the essential nutrients needed in the proper amount for an optimum performance (Duntonvets 2018) [22].

Rabbits are hindgut fermenters, that is, they digest plant-based food in their cecum and colon using microbial fermentation, enabling efficient fiber utilization post-gastric digestion (Anna, 2011) [10]. Rabbits practice cecotrophy, the reingestion of soft, nutrient-enriched faeces produced via the fusus coli (a specialized section of the colon). This process, which usually takes place at night, enables the animal to absorb more vitamins, VFAs, and microbial proteins that were produced in the cecum (Kohles, 2022) [34]. For rabbits, getting enough dietary fiber is crucial because digestible fiber promotes fermentation activity and cecal health, whereas indigestible fiber promotes Gastrointestinal motility and tooth wear (Joerg, 2021).

2.3 Non-Conventional Feed Resources (NCFRs)

Feed ingredients like Agro-industrial by-products and Crop residues are generated during processing of agricultural commodities (e.g., peeling, pressing and milling, brewing, drying). Typical examples include cassava peels, citrus pulp, palm kernel cake, brewers' grains, and watermelon rinds (Abiola-Olagunju and Olusoji, 2015) [1].

When processed properly, many NCFRs retain an appreciable nutritive value and can be incorporated into animal diets to reduce feed–food competition and lower feed costs (Jumare *et al*., 2024) [31]. Most NCFRs are rich in fiber, with moderate protein and useful minerals and vitamins. For instance, dried watermelon rind flour typically contains approximately 10.2% crude protein and 17.4% crude fiber, alongside substantial ash, micronutrients, minerals and vitamins. It also concentrates **citrulline**, a nitric-oxide-related amino acid relevant to antioxidant status and vasodilation (Ashoka *et al.*, 2022; Gwana *et al*., 2014).

Olafadehan *et al.,* (2012) and Kazemi (2025) reported that to ensure safety and performance, processing is required due to variability in nutrient composition, moisture, and anti-nutritional factors (ANFs). Drying and grinding are common, scalable techniques for extending shelf life and reducing spoiling; ensiling/fermentation to improve digestibility, stabilize nutrients, and inhibit pathogens; and detoxification targeted to specific ANFs. Retting and sun-drying cassava peels are successful at lowering cyanogenic potential; fermentation and combined acid-hydrolysis techniques have also reduced cyanide levels in cassava products intended for feed by more than 90%. Cassava by-products and citrus pulp provide readily fermentable carbohydrates and functional polysaccharides that support hindgut fermentation in rabbits, while brewers' grains and palm kernel cake contribute both fiber and protein fractions suitable for herbivorous monogastrics when diets are properly balanced (FAO, 2014) [24].

2.4 Watermelon Rind, an Important Example of NCFRs

A rind is a thick firm outer coating usually found in fruits. The skin of a watermelon is smooth, with a dark green or pale green stripes rind, depending on the variety. Watermelon rind is edible and contains variety of nutrients (Olawale, 2024) [39]. It is one of the many unwanted by-products produced by eateries, fruit juice manufacturers and food industry, of which a substancial amount of it is trashed into the environment thereby polluting the environment (Otu *et al.,* 2021).

According to Petkowicz *et al.,* (2017), watermelon has been studied to be a source of nutritional feed ingredients prviding essential antioxidants, amino acids, pection and especially citrulline which serves as a means of protection from free radical damage. Furthermore, Citrulline transforms into arginine, an amino acid that is essential to the immune system, heart and circulatory system (Rimanado and Perkins-Veazie, 2015).

Watermelon rind contains 93.8% moisture, 0.49% ash, 0.1% nitrogen, and 1.2% sugar. The fiber of watermelon peel contains about 20% cellulose, 23% hemicellulose, 10% lignin, 13% pectin, and contains 2.2 mg/g of dry matter weight of the amino acid citrulline (Nahid *et al.,* 2022). The main element that speeds up microbial spoiling and food deterioration is water (Sewald and DeVries, 2015) [42]. The fresh watermelon rind deteriorates due to improper treatment of watermelon by-products following fruit processing, which quickly causes significant physical damage and loss. Therefore, to extend its shelf life, watermelon must be processed by drying it and lowering its water content then turning it into powder (Ho, 2016) [28].

Watermelon rinds are a good source of fiber, which can help to promote gut health and regularity and can be enjoyed by both humans and livestock. Ashoka *et al.* (2022), researched on a particular drying parameter for watermelon rind by subjecting it to dehydration in an oven at 60°C up to 12 hours. It was then observed that there is high moisture loss and the dehydrated ratio was found to be 5.59, leaving the moisture content to remain 12.17%. The research was further continued by looking into the proximate composition of watermelon rinds powder and the result is shown in (Table 1).

The nutritional composition of dried watermelon rinds depends on factors like the drying method, the ripeness of the watermelon, and the specific variety of watermelon used.

Table 1: Proximate and mineral composition of watermelon rind flour (100g)

Nutrients	Watermelon Rind Powder
Protein	10.18g
Fat	2.37g
Crude fibre	17.44g
Ash	11.82g
Carbohydrates	46.02g
Ascorbic acid	10.25mg
Calcium	254.25mg
Phosphorus	268.28mg
Magnesium	345.48mg
Iron	12.76mg

(Ashoka *et al.,* 2022).

3. Functional Properties

Modifying rabbit diets with NCFRs can yield functional meat results enhancing fatty-acid profile, oxidative stability, color, water retention, and eventually shelf life without compromising performance when inclusion rates and processing are suitably managed (McNitt *et al*., 2013). Rabbit meat is naturally low in fat and high in PUFA. Targeted diet methods can improve this profile even more, making rabbit a useful food for human health, high in omega-3 polyunsaturated fatty acid (n-3 PUFA), low in sodium and cholesterol). (Dalle Zotte and Szendrő, 2011)

[18].

Meat quality includes characteristics such as texture, flavor, color, juiciness, and nutritional composition (Mayulu *et al*., 2019; Akhigbe and Akaeze, 2023). In rabbits, these characteristics are significantly affected by nutrition, breed, age, and handling techniques. NCFRs (non-conventional feed resources), especially those rich in bioactive chemicals, have demonstrated the ability to improve some meat quality parameters (Dalle Zotte and Szendrő, 2011) [18].

3.1 Physico-Chemical and Sensory Traits

In a recent study by Olawale (2024) [39], rabbits were fed diets containing 0%, 5%, 10%, and 15% dried watermelon rinds. The study revealed that inclusion of the rind had no adverse effect on the physico-chemical and sensory parameters of rabbit meat. Notably:

- Tenderness and overall acceptability improved significantly at **15%** inclusion.
- Cooking loss and refrigeration loss decreased with increasing rind levels.
- Color stability (L*, a*, b*) was higher in supplemented diets, indicating improved freshness.
- Water absorptive power decreased slightly, suggesting low moisture retention during processing.

These findings support the functional value of watermelon rinds in improving the sensory appeal and storage properties of rabbit meat, aligning with broader evidence the findings of Palumbo *et al.,* (2025) and Corino *et al.,* (1999) that dietary antioxidants and bioactive-rich by-products like vitamin E and polyphenol sources can enhance oxidative stability and color in rabbit meat.

3.2 Lipid profile enrichment (n-3 PUFA)

Integrating n-3 sources (e.g., extruded flaxseed; specific microalgae) into rabbit diets reliably enhances long-chain n-3 PUFA deposition in meat, validating diet-to-meat transfer and endorsing functional labeling (Agradi *et al.,* 2023). For example, adding 5% extruded flaxseed, with or without a little amount of brown algae, increased thigh-meat n-3 PUFA; packaging treatments were then utilized to maintain quality throughout storage (Castrica *et al*., 2025).

3.3 Natural antioxidants and oxidative stability

Due to the potential for PUFA enrichment to hasten oxidation, it is essential to combine n-3 sources with antioxidants. Increased dietary vitamin E safeguards PUFA-enriched rabbit meat from oxidative degradation, enhancing color stability and sensory appeal. (Eiben *et al*., 2011; Palumbo *et al*., 2025). Polyphenol-rich plant by-products, such as grape pomace or grape seeds, reduce lipid oxidation and can sustain sensory characteristics at modest inclusions (about 5–10%), while promoting growth. (Carta *et al*., 2025).

3.4 Feed additives e.g fish oil, lycopene and organic selenium

Danuta *et al.,* (2020) concluded that although essential fatty acids possess significant nutritional benefits, it is crucial to prevent lipid oxidation and adverse impacts on the sensory attributes of meat and meat products during processing and subsequent storage Supplementation with fish oil was advantageous solely for nutritional purposes, as it reduced the Σn-6/Σn-3 ratio. The usage of selenium and lycopene together shown antioxidant action, slowing the fat oxidation process. Despite an increase in animal muscle mass and a high level of fatty acid from the n-3 family in meat, its low sensory quality and significant oxidative alterations in muscle fat indicate that enriching rabbit fodder with fish oil is impractical.

3.5 Fruit-processing residues (e.g., watermelon rind)

Watermelon rind (WR), rich in minerals and bioactives such as citrulline has a documented proximate composition that is suitable for monogastric feeding (Ashoka *et al*., 2022; Otu *et al*., 2021). Although there is currently little data on rabbit meat, WR has proved safety and functionality in related monogastric applications and has potential to support oxidative stability (Rimando and Perkins-Veazie, 2005).

4. Sustainability Implications

Integrating NCFRSs into rabbit diets offers environmental**,** economic or social**,** and food security benefits that align with circular-economy principles and feed–food competition reduction.

4.1 Environmental implications

NCFRs such as citrus pulp, brewers' spent grain (BSG), palm kernel cake, and watermelon rind represent significant fractions of food-processing residues that, if unmanaged, contribute heavily to solid waste streams (Abiola-Olagunju and Olusoji, 2015) [1]. For example, the global brewing industry generates over 36 million tonnes of BSG annually, and landfilling each tonne can release about 513 kg CO_2, underscoring the potential environmental burden when such residues are discarded (PMC, 2023). Incorporating these feed resources into rabbit feed reduces the volume of organic material requiring disposal while simultaneously offsetting reliance on conventional cereals (Otu *et al*., 2021; Jumare *et al*., 2024 [31]). In Nigeria, large volumes of watermelon rinds are discarded daily from eateries and juice processors; drying and milling these rinds into flour not only curbs waste accumulation but also creates an affordable feed resource (Ashoka *et al*., 2022; Olawale, 2024 [39]).

Uncontrolled disposal of agro-industrial residues contributes to air, water, and soil pollution through leachate formation, methane emissions, and microbial contamination (Detritus Journal, 2023) [20]. By valorizing these residues as feed ingredients, pollution risks are significantly mitigated. For instance, ensiling or fermenting citrus pulp improves its storage stability while preventing nutrient-rich waste from leaching into water bodies (Serra *et al*., 2017). Similarly, utilizing BSG and cassava peels in feed chains reduces greenhouse gas (GHG) emissions otherwise produced during open dumping or incineration (FAO, 2014) [24]. In addition, processing watermelon rind into dried powder prevents microbial spoilage and environmental littering in urban markets, thereby addressing both waste management and public health concerns (Ho, 2016; Sewald and DeVries, 2015) [28, 42].

The integration of NCFRs into rabbit diets exemplifies the circular bioeconomy, where waste streams are reintroduced into the production chain, thereby extending resource life cycles and lowering the environmental footprint of livestock feeding (Frontiers, 2023; Wiley Online Library, 2022). In contrast to cereal grains that necessitate specific land, water, and energy resources, by-products incur minimal marginal environmental costs, as they are co-products of established food enterprises. (FAO, 2023) [25]. Their valorization reduces pressure on arable land and lowers the embedded impacts of feed production, including transport and energy use (Muscat *et al*., 2021) [36]. In Africa, incorporating locally available NCFRs into rabbit production systems has been highlighted as a practical strategy to enhance sustainability while reducing dependence on imported feed resources (Ajagbe *et al*., 2022 [5]; Klopfenstein *et al*., 2013). Thus, valorization of residues like citrus pulp, brewers' grains, and watermelon rind supports not only feed sustainability but also broader circular-economy goals of resource efficiency and waste minimization.

4.2 Economic or Social implications

Feed constitutes the largest component of livestock production expenses, accounting for 60–80% of total production costs in many intensive and smallholder systems (Adeyemi *et al*., 2014 [2]; Klopfenstein *et al*., 2013; FAO, 2014 [24]). Incorporating NCFRs into rabbit diets can substantially reduce this burden by replacing part of the costly conventional ingredients such as maize and soybean meal with low-cost, readily available alternatives. For example, cassava peels and palm kernel cake, when properly detoxified and processed, have been successfully used to substitute cereal grains without impairing growth or carcass traits (Jumare *et al*., 2024; Abiola-Olagunju and Olusoji, 2015) [31, 1]. Similarly, dried watermelon rind, abundant in Nigeria has been reported to maintain rabbit meat quality at inclusion levels up to 15%, demonstrating its potential as a cost-effective feedstuff (Olawale, 2024) [39]. By reducing dependency on imported cereals, NCFRSs enhance the economic viability of rabbit farming in resource-constrained environments.

The use of NCFRs not only reduces production costs but also enhances profitability, making rabbit farming more attractive and accessible to smallholders. Studies in Nigeria have shown that the integration of agro-industrial residues in rabbit diets can increase gross margins and lower entry barriers for youth and rural farmers, who often face capital constraints (Ajagbe *et al*., 2022; Olawale, 2024) [5, 39]. Because rabbits are efficient converters of fibrous feeds, their compatibility with NCFRs enables cost-effective meat production compared with ruminants or poultry (Dalle Zotte and Szendrő, 2011) [18]. This affordability supports household-level food production and contributes to income diversification in rural settings, ultimately improving livelihoods and resilience to economic shocks.

Valorization of by-products for animal feeding can generate positive spillover effects in rural economies by fostering linkages between farmers and agro-processors**.** For example, fruit juice industries, breweries, and cassava processing plants produce large volumes of residues (e.g., citrus pulp, brewers' spent grains, cassava peels), which can be collected, dried, and sold as feed ingredients. This creates micro-enterprises in waste collection, drying, grinding, and distribution, stimulating rural employment and entrepreneurship (Muscat *et al*., 2021; FAO, 2023) [36, 25]. Furthermore, integrating these residues into feed chains supports sustainable waste management, reducing the environmental burden of organic waste while providing low-cost resources for livestock keepers (Detritus Journal, 2023) [20]. In regions where unemployment and underutilized biomass coincide, such circular linkages contribute to rural development, improved sanitation, and inclusive growth.

4.3 Food Security implications

A notable contribution of NCFRs to food security is the enhancement of local feed resource availability. In regions such as sub-Saharan Africa, where competition for maize and other grains between humans and livestock is intense, redirecting residues like cassava peels, citrus pulp, and watermelon rind into feed alleviates dependence on staple crops (Nicholas, 2023 [37]; Teguia *et al*., 2004). By processing these residues through drying, grinding, or fermentation their shelf life and nutritional quality are improved, ensuring a more stable supply of feed across seasons (Ho, 2016; Hasanin *et al*., 2020) [28, 27]. This localized availability reduces vulnerability to disruptions in global grain supply and supports continuous livestock production, even during periods of cereal scarcity (Ajagbe *et al*., 2022) [5].

Rabbit meat provides a lean, highly digestible, and nutritionally superior protein source compared with other conventional meats. With crude protein levels above 20%, low fat (1–3%), and high concentrations of polyunsaturated fatty acids (PUFAs), rabbit meat offers health benefits that align with consumer demand for functional foods (Dalle Zotte and Szendrő, 2011; ARBA, 2023) [18, 9]. Integrating NCFRs into rabbit production systems ensures that high-quality meat remains affordable and accessible, particularly in developing countries where animal protein intake often falls below recommended levels (Ajala and Balogun, 2004) [6]. Diversifying the protein basket with rabbit meat reduces reliance on beef, poultry, and fish, thereby contributing to dietary security and nutritional resilience.

Climate variability and market volatility present increasing challenges to global feed and food systems. Rising costs of conventional feed ingredients, such as maize and soybean, make smallholder livestock production particularly vulnerable (Klopfenstein *et al*., 2013; Nicholas, 2023 [37]). The inclusion of NCFRs into rabbit diets reduces this dependency and buffers production systems against price fluctuations in global grain markets. Moreover, utilizing locally available residues builds resilience to climate shocks, since the production of by-products (e.g., fruit rinds, cassava residues, and oilseed cakes) often continues even under conditions where cereal crop yields may be constrained. In this way, NCFRs-based feeding strategies not only enhance household-level food security but also contribute to system-wide resilience by stabilizing both input and output markets in the rabbit value chain (Okai *et al*., 2009 [38]; Otu *et al*., 2021).

5. Research Gaps and Future Perspectives

Despite the expanding literature on the use of non-conventional feed resources (NCFRS) and agro-industrial by-products in rabbit nutrition, there are still significant gaps that necessitates further research. Most studies on NCFRs in rabbit diets have focused on growth performance, nutrient utilization, and carcass yield (Okai *et al*., 2009; Jumare *et al*., 2024) [38, 31]. Far fewer have examined how these feed resources influence physico-chemical traits, sensory attributes, and functional properties of rabbit meat. For example, while watermelon rind has been evaluated for its effects on performance in monogastrics (Otu *et al*., 2021), only limited work including Olawale (2024) [39] directly assesses its impact on rabbit meat quality. Broader studies are required to establish standardized relationships between

NCFRS inclusion and key meat quality indices such as tenderness, water-holding capacity, lipid oxidation, and nutritional composition.

There is also variability in nutrient composition and processing methods. Agro-industrial residues vary widely in nutrient profile depending on crop variety, season, and processing method (Abiola-Olagunju and Olusoji, 2015; Hasanin *et al*., 2020) [1, 27]. Such variability limits consistency and predictability of outcomes when used in rabbit diets. Moreover, while drying, ensiling, and fermentation have been shown to improve stability and safety (Ho, 2016; FAO, 2014) [28, 24], more research is needed to identify low-cost, scalable processing techniques that minimize anti-nutritional factors and enhance bioavailability of nutrients across diverse contexts.

Consumer perception and market acceptance is also a concern. Although rabbit meat is recognized as a lean and functional protein source (Dalle Zotte and Szendrő, 2011) [18], its market penetration remains low in many regions, including Nigeria, due in part to cultural preferences and lack of awareness (Cullere and Dalle Zotte, 2018) [17]. There is limited information on consumer acceptance of rabbit meat produced with NCFRs, particularly regarding perceptions of quality, safety, and nutritional value. Future studies should integrate sensory panels, consumer surveys, and willingness-to-pay analyses to better understand market opportunities and constraints.

While NCFRS use clearly contributes to waste reduction and cost savings, there is a lack of quantitative life-cycle assessments (LCA) evaluating the environmental benefits of incorporating these by-products into rabbit production (De Miguel *et al*., 2018; Bava *et al*., 2025) [19, 11]. Future research should explore the carbon, land, and water footprints of NCFRS-based diets in comparison with conventional cereal-based formulations, to provide policymakers and industry stakeholders with robust sustainability metrics.

Research in other monogastrics (poultry, pigs) has demonstrated the potential of NCFRSs to improve both performance and meat quality traits (Klopfenstein *et al*., 2013). Comparative studies across species would help to position rabbits within the broader context of sustainable livestock production, leveraging their unique digestive physiology and efficiency in converting fibrous feeds. Interdisciplinary approaches linking animal science, food technology, and environmental science are essential for maximizing the functional and sustainable potential of NCFRs in rabbit nutrition.

6. Conclusion

The integration of non-conventional feed resources (NCFRs) such as watermelon rind, citrus pulp, cassava peels, and brewers' grains into rabbit diets presents a sustainable approach to reducing feed costs, valorizing agro-industrial residues, and enhancing meat quality. Evidence shows that these by-products can improve functional properties of rabbit meat, including antioxidant stability, lipid profile, and sensory attributes, while supporting environmental sustainability and food security through waste reduction and protein diversification. Nonetheless, challenges such as nutrient variability, limited data on meat squality outcomes, and gaps in consumer acceptance remain. Future research should focus on standardized processing techniques, long-term feeding trials, life-cycle sustainability assessments, and market studies to guide adoption. Strengthened collaboration between researchers, policymakers, and industry stakeholders is recommended to unlock the full potential of NCFRs in advancing functional meat production and sustainable rabbit farming systems.

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