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# Solid-State Fermentation of Crop Residues and Agro-Industrial Byproducts in Small Ruminant Production: A Review

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**Abstract:** The increasing competition for major feed ingredients such as maize due to world crisis, caused by the high cost and scarcity of these conventional feed ingredients due to climate changes have necessitated the exploration of indigestible alternative feed resources for sustainable small ruminant production. Crop residues and agro-industrial by-products (AIBPs) are highly abundant, cost-effective, and readily available feed options that can enhance livestock production while minimizing environmental waste. This systematic review evaluates the nutritive effects, physiological responses, and reproductive parameters associated with the inclusion of crop residues and AIBPs in small ruminant diets. The review synthesizes findings from various studies, highlighting their impact on feed intake, digestibility, growth performance, haematological and biochemical indices, reproductive efficiency, and overall productivity. While these alternative feed resources can improve nutrient availability and animal performance, challenges such as anti-nutritional factors and variability in nutrient composition must be addressed through appropriate processing techniques. The findings suggest adequate utilization of crop residues and AIBPs, alongside suitable supplementation, did not necessarily affect the production indices, thereby enhancing small ruminant production, reduce feeding costs, and contribute to sustainable livestock farming as well as decrease the potency for environmental pollution.

**Keywords:** Crop residues; agro-industrial by-products; sheep and goat production; sustainable livestock farming

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## 1. Introduction

In agricultural systems of developing nations, small ruminants hold a significant ecological and economic niche [1,2]. They supply food security, a steady household income, fiber and skins, animal protein (meat and milk), and draught power in the highlands [1]. In terms of size, integration of production systems in farming systems, and environmental adaptation and interaction, small ruminants also have several benefits over large ruminants [1,3]. Goats are the second most significant livestock species in Nigeria due to their population. In the tropics and subtropics, India is the only country with more goats than Nigeria, with 34.5 million goats in the country [4]. Nonetheless, smallholder farmers own the great bulk of the goats, leaving them to forage for food on the streets. Consequently, the issue of poor or insufficient feeding results in low reproductive and productive performance of the animals [5,6].

Ruminants in the tropics are grown mostly on grass, which is naturally low in nutrients and digestibility and unavailable during the off-season [7]. Natural pasture availability varies seasonally; it is typically more abundant, succulent, and highly nutritious during the rainy season, which runs from May to November, than during the dry season, which runs from November to April [8]. These natural pastures become fibrous, scarce, and devoid of the most important nutrients during the dry season, including protein, energy, minerals, and vitamins. These nutrients are necessary for increased rumen microbial fermentation, which produces volatile fatty acids and enhance the host animals' ability to produce and reproduce [8]. Due to the fibrous and lignified character of the available pasture, which restricts intake, digestibility, and utilization, ruminant animals' performance—which depends on the subpar native pasture—is severely hampered during this crucial dry period [9].

Due to increased crop production to feed the world's growing population, Nigeria has an abundance of agro-industrial by-products (AIBs) and crop leftovers. Sugarcane scraps are among these AIBs. When the cane is being processed or chewed to extract the cane juice, the rind of the stem is scraped off with a sharp knife to make it easier to access the soft parenchyma tissue underneath. This easily accessible waste is known as sugarcane scrapings (SC).

These scrapings are mostly heaped and sometimes burnt or left thereby constituting an environmental pollution problem [10,11]. However, previous attempts [12,13] to incorporate them in livestock feeds resulted in impressive results. Sugarcane scrapings have been used as a non-conventional feed resource in replacing energy sources such as maize bran and rice bran in monogastric diets and ruminant diets [3,12–14]. High energy and crude fibre (CF) but low crude protein (CP) contents have been reported for SC [16,17]. The high CF and low CP of SC necessitate some form of treatments or processing to enhance their nutritive value.

By decreasing the proportion of fiber and increasing the protein content, biodegradation techniques have been used to improve the nutritional quality of many low-quality farm wastes. This has resulted in fibrous materials that are rich in soluble carbohydrates, which are useful nutrients for livestock [11,18–20]. The feed value of low-quality, unconventional components used in animal feed formulation has been increased by the application of biodegradation processes such microbial fermentation, solid state fermentation with fungus, and enzyme supplementation.

According to Anaso et al [11] and Ayoade et al. [16], Using less expensive feed supplies for animal production might lower the market price of animals and their products in Nigeria. This will go a long way in making animal products available and affordable and thus improve the dwindling animal protein intake in final consumers (in terms of meat, milk and other animal products).

## 2. Methodology

### *2.1. Search Strategy*

Scopus, Web of Science, PubMed, and Google Scholar were the four main databases used for a thorough literature search. The search encompassed research published from 2000 to 2025, guaranteeing the inclusion of both seminal and contemporary papers. Search terms were combined using Boolean operators and included keywords such as "small ruminants," "goats," "sheep," "crop residues," "agro-industrial by-products (AIBPs)," "biodegradation," "fermentation," "sugarcane scrapings," "cassava peels," and "alternative feed resources." Reference lists of key articles and review papers were also hand-searched to identify additional relevant studies not captured in the database searches. Studies that fulfilled the requirements listed in Table 1 were eligible for inclusion.

**Table 1.** Eligibility Criteria for Study Selection

| Categories | Inclusion Criteria | Exclusion Criteria |
|---|---|---|
| **Species** | Experimental trials on small ruminants (sheep and goats). | Studies on non-ruminants or large ruminants (cattle, buffaloes, camels). |
| **Intervention** | Diets containing crop residues and/or agro-industrial by-products, with or without biological or chemical processing. | Diets not involving crop residues or agro-industrial by-products. |

| | | |
|---|---|---|
| **Outcomes** | Reported effects on at least one of the following: feed intake, nutrient digestibility, growth performance, haematological or biochemical indices, reproductive traits, carcass/meat quality, or thermoregulatory responses. | Studies not reporting relevant animal performance, physiological, or product quality outcomes. |
| **Study Type** | Peer-reviewed original research articles, conference proceedings, or theses published in English. | Opinion papers, commentaries, reviews, duplicates, or studies with incomplete methodology. |

*2.2. Screening Process*

In the first database search, 312 articles were found. Following the elimination of duplicates (n = 67), 245 articles were left for screening of the titles and abstracts. Out of these, 156 publications were disqualified for not meeting the requirements for inclusion (e.g., inappropriate species, results unrelated to animal nutrition, or inadequate methodological description). A total of 62 studies were ultimately included in this review after the full texts of 89 articles were evaluated for eligibility. Using a standardized template, data were extracted in a methodical manner. Table 2 provides an overview of the variables taken into account.

**Table 2**. Variables extracted from studies included in the review.

| Category | Extracted Variables |
|---|---|
| Study characteristics | Author(s), year of publication, country, species/breed |
| Experimental design | Number of animals, age, sex, treatment groups, duration of feeding trial |
| Dietary composition | Type and level of crop residues/AIBPs, processing method (biodegradation, fungal treatment, fermentation, enzyme supplementation) |
| Measured outcomes | Feed intake, digestibility, growth performance, carcass yield, biochemical/haematological indices, reproductive performance, thermoregulation |

*2.3. Quality Assessment*

A modified version of SYRCLE's risk of bias tool for animal experiments was used to assess the methodological quality of the included research. Each study was assessed for clarity of experimental design, randomization procedures, control group adequacy, sample size justification, and completeness of outcome reporting. The risk of bias in the studies was categorized as low, moderate, or high. Discrepancies between assessors were resolved by discussion until consensus was reached.

## 3. Agro-Industrial Byproducts and Alternative Feedstuffs for Livestock Production

Following Nigeria's agro-industrial revolution, a large number of industrial and agricultural byproducts became available in such large quantities that they created a waste disposal issue [21]. The local demand for agro-industrial by-products in the late 1960s and early 1970s could not keep up with the supply. As a result, Fetuga and Ogunfowora [22] suggested the export of these goods. Nevertheless, these agro-industrial byproducts have gained a lot of attention in the cattle feeding industry over time. Nowadays, animal feed is typically made from agricultural byproducts, such as wheat offal, cocoa husks, cassava peels, and maize cobs. Once regarded as waste, these by-products are now being transformed into animal protein for human consumption, which is a change from the previous norm. Additionally, industrial by-products such molasses from the sugar industry, wheat and maize offals from the flour industry, and dried brewer's grains from the brewing industry are no longer burned because they were deemed pollutants [23]. They are now regarded as feed commodities and are typically sold for high prices, particularly during the dry season.

According to research by Anaso et al. [11], using, biodegrading, and feeding abundantly available AIBPs/crop residues in Nigeria will help alleviate the feed shortage issue for cattle caused by ongoing farmer-herder conflicts, armed banditry, and the present global pandemic (Covid-19). The threat posed by small holder livestock production systems can be reduced by ensuring year-round feed availability for animals through the biodegradation and preservation of AIBPs. There is a wealth of empirical data supporting the use of biodegraded AIBPs as a protein or energy source in cattle diets to increase production without endangering health.

Resources can be recycled more efficiently in animal production enterprises when livestock and agricultural byproducts are integrated. Nigerian government, commercial, and individual farms create large amounts of crop residues that are repeatedly not used. The majority are burned, but some are allowed to break down on the field, which may increase soil fertility anyhow. According to O'Donovah [24], animals given agro-industrial byproducts showed notable weight increases. Agro-industrial by-products are widely available and available at low price, which could boost production and lower the cost of compound feed without negatively impacting animal performance. Finding substitute feed ingredients has become more crucial in order to lessen competition between humans and livestock due to the growing human population and the resulting high cost and demand for traditional feedstuffs like soybean meal and groundnut cake [23].

### *3.1. Sugarcane Scraping as an Agro-Industrial Byproduct for Livestock Feed*

In animal diets, agro-industrial wastes like bagasse and sugarcane scrapings can be easily used as unconventional feed resources to replace energy sources like maize bran or rice bran [3,13]. The high fiber content of agro-waste products needs to be broken down and its nutritional composition modified through processing in order to increase its use in livestock diets. When sugarcane is handled locally by peeling, the indigenous chew the sugarcane and toss the peels everywhere. Saleh [25] observed that sugarcane peels produced in Nigeria are abundantly available throughout the dry season (October to February) in northern Nigeria. If sugarcane peels are discarded into the street without being used, they might pollute the environment. These peels, also known as scrapings, clog water drainage systems and streets, rendering them unclean and adding to the excessive buildup of solid waste in cities. When they catch fire, they can pollute the air, posing a risk to human health and the health of animals by causing acute respiratory illnesses and overall discomfort [11]. They can be harvested, processed, and utilized as an inexpensive substitute ingredient for animal feed in place of this unpleasant circumstance, which would lessen the issue of environmental risks.

Various processing methods have been reported in achieving nutritional improvement and reduction in fibre content of alternative fibrous or lignocellulosic unconventional feedstuffs. Among these include mechanical and chemical treatments, exogenous enzymes, fermentation, and fungal-based biodegradation [2,17,26]. Several researchers have reported employing rumen fluid to digest sugarcane wastes and other agro-industrial wastes both in vivo and in vitro for both ruminant and monogastric animals [14,27–29].

### *3.2. Enhancing the Nutritive Value of Agro-Industrial Wastes and Crop Residues through Solid-State Fermentation and Biodegradation*

Solid state fermentation (SSF), as defined by Zadražil et al. [30], is a process that produces a high-quality standardized product (different from composting) by breaking down solid substrates using known pure or mixed cultures of microorganisms (primarily fungi that can grow on and through the substrate) under controlled conditions. In the multifactorial process known as SSF, the fungus and its enzymes, the physical structure of the substrate, the physical aspects of fermentation and culture, and the nutritional conditions all have a major impact on controlling the lignin breakdown and the digestibility of fermented substrate [31]. When AIBP's are intended for ruminant nutrition, the bioconversion process must play a part in increasing the digestibility of lignocellulose. Enriching the finished product with microbial protein is one way to demonstrate the suggested biological upgrading of lignocellulosic into animal feed [32]. With the contemporary buildup of digestible materials, there is a noticeable breakdown of lignin that releases nutrients from the lignocellulose matrix [30]. Increasing the delignification of a lignocellulosic substrate requires improving the rate and specificity of lignin molecule degradation while preventing polysaccharide consumption [33]. However, little is known about the mechanisms causing selective delignification [33–35].

Olafadehan et al. [36] experimented to study the effect of the white rot fungi (Pleurotus ostreatus) degradation or solid-state fermentation of sugarcane scrapings on the chemical composition and anti-nutritional constituents. Where sterilised sugarcane scrapings were inoculated with Pleurotus ostreatus and allowed to ferment for 21 days. The result indicated that the biodegradation of sugarcane scrapings increased the crude protein, ether extract, ash, nitrogen free extract, metabolizable energy concentrations, and decreased dry matter, crude fibre, neutral detergent fibre and the secondary metabolites (saponins, oxalate, phytate, tannins and flavonoids) concentrations relative to the non-biodegraded sugarcane scrapings. Due to the increment in the crude protein and metabolizable energy concentrations, and reduction in the fibre and secondary metabolites concentrations, it was concluded that biodegradation of sugarcane scrapings with Pleurotus ostreatus could be used to enhance the nutritive potential of sugarcane scrapings.

A significant amount of lignocellulosic residues has accumulated globally as a result of the over-improvement of agro-industrial operations in recent years. The most prevalent agricultural residues worldwide are lignocellulosic materials. Photosynthesis continuously replenishes them. Therefore, microbes that can break down these substances—such as fungus, actinomycetes, and other bacteria—play a crucial role in making them more digestible. A novel technique for increasing the digestibility of agricultural residues is biological treatment [3,10,11,37].

Despite the fact that all of the major fungal taxa contain cellulolytic fungi [38,39], it appears that only a small number of microorganisms are able to manufacture ligninolytic enzymes. White-rot fungi are the most effective microbes for breaking down lignin [40,41].

By partially breaking down the lignin-carbohydrate complex, some microbes (specifically, fungi called basidiomycetes) can disrupt plant cell walls, which improves their utilization in the rumen by increasing the amount of fermentable energy available to ruminal microbes [11]. This function has been used to explain the ability of biological treatments. Decomposed residue turns white because white-rot fungi may break down lignin without impacting a large amount of cellulose and hemicellulose [37]. Unaltered lignin polymers are attacked by white rot fungi (WRF), which results in the breakage of aromatic rings and inter-lignol linkages [11].

Pleurotus species is the most studied fungus because it enhanced the nutritional value and digestibility of straws and other products [43,44], even though numerous species of complex fungi have ligninolytic activity [45]. Compared to the original material, these biodegraded straws had a higher amount of ash, less cellulose and lignin, more protein, and more free sugars [46].

After Pleurotus ostreatus mushrooms were cultivated and harvested, Anaso [47] study found that the in vitro dry matter digestibility (IVD) of discarded wheat straw increased by 4.4 to 8.9%. According to Anaso [48], P. ostreatus's 30-day SSF of wheat straw raised the in vitro dry matter digestibility from 14.3 to 29.5% while also dramatically lowering the lignin concentration. According to Ramirez-Bribiesca et al. [49], P. ostreatus treatment of maize straw for 15 days reduced neutral detergent fiber (14.5%) and increased crude protein (39.5%), soluble protein (165%), soluble carbs (621%), and ash (1883.32%).

*3.3. Voluntary Feed Intake of Ruminants Fed Sugarcane Scrapings And Treated Agricultural Wastes Containing Diets*

The impact of replacing maize bran with Pleurotus ostreatus biodegraded sugarcane scrapings (BSS) on the growth performance and reproductive capacity of Kano Brown bucks was assessed by Anaso et al. [3]. Intakes of DM, crude protein, and organic matter varied in the following order, according to the results: 15% BSS > 0% BSS > 30% BSS. The 15% BSS diet had a higher final BW than the 0 and 30% BSS diets. Although 15% BSS had a greater effect and was advised, it was shown that up to 30% biodegraded sugarcane scrapings may be included in a bucks' entire diet without having a detrimental effect on their final body weight or semen quality.

Saleh and Maigandi [50] conducted an experiment to evaluate the nutritional potentials of sugarcane peels in Yankasa sheep by replacing cowpea husk with 0, 15, 30 and 45% of the peels. Results of this experiment showed that both the feed and nutrient intakes were not affected by the treatments. Olafadehan and Okoye [51] reported non-significance difference in the daily intakes of dry matter, crude protein, organic matter, crude fibre, total carbohydrate and neutral detergent fibre by Red Sokoto goats fed urea treated ensiled cowpea husk substituted for dried brewers' grain.

The feeding value of treated and untreated sugarcane bagasse, with or without enzyme supplementation, in a total mixed ration was also investigated by Mijinyau et al. [52]. Sokoto bucks in red. Two dietary regimens were given sixteen dollars, each containing four dollars, and a life weight of 10±2 kg. When compared to bucks fed untreated bagasse without enzyme supplementation, the feed consumption results of bucks fed treated bagasse with enzyme supplementation were noticeably greater. Saleh and Abubakar [4] demonstrated that the nutrient intake of Kano Brown bucks fed diets containing sugarcane peels meal increased as the amount of the peels meal substituted for wheat offal increased up to 75%. They came to the conclusion that the goats' diets could contain up to 75% sugarcane peel meal in place of wheat offal. This discovery supported its potential as a substitute goat feed ingredient. Thus, adding sugarcane peels to ruminant diets might increase livestock productivity in Nigeria and reduce urban solid waste [11].

Six dietary treatment groups of goats were fed different amounts of maize offal in a study by Wuonor and Ayoade [53]. These groups included brewer's yeast slurry mixture, ad libitum, untreated rice straw (UTRS), and rice straw treated with Pleurotus tuber-regium. Daily feed intake and daily body weight gain were found to be significantly (P=.05) enhanced by the fungal treatment of rice straw in conjunction with a mixture of brewer's yeast and maize offal. The feeding regimen was found to be a dependable dry season feed because it greatly increased feed intake, body weight gain, water intake, and feed conversion ratio when goats in confinement were fed a combination of rice straw treated with Pleurotus tuber-regium and maize offal: brewer yeast slurry mixture.

*3.4. Effect of Feeding Biodegraded Agricultural Wastes on Blood Profile of Ruminants*

According to Anaso et al. [6], haematological indicators are blood components that are commonly evaluated to determine an animal's health. In an experiment to determine whether feeding Pleurotus ostreatus BSS would negatively affect the body thermoregulation and serum metabolic profile of goats, Olafadehan et al. [15] demonstrated that serum total protein, albumin, globulin, and albumin: globulin ratio were higher by dietary treatments. Twenty-one healthy male Kano Brown bucks (6–7 months of age; 9.44 ± 0.39 kg mean body weight) were stratified based on their BW into three treatment groups containing 0 (T1), 15 (T2), and 30% (T3) of BSS in a completely randomized design.

The influence of giving BSS diets on the feed intake and haematology of growing goats, as well as the impacts of BSS with Pleurotus ostreatus on their chemical and phytochemical makeup, were investigated by Anaso and Olafadehan [2]. In a fully randomized design, twenty-one healthy Kano Brown bucklings (6–7 months old, average weight 9.40 ± 0.39 kg) were divided into three diets for 16 weeks, with BSS inclusion levels of 0% (T1), 15% (T2), and 30% (T3). In comparison to untreated sugarcane scrapings, the biodegradation of SS increased the quantity of crude protein, ether extract, and non-structural carbohydrates while decreasing dry matter, fiber fractions, metabolizable energy, and phytochemical levels. T2 had the highest nutrient intake, with the exception of non-structural carbs. Red blood cell counts were significantly higher in T2 and T3, while haemoglobin concentration and packed cell volume were similarly higher in T2. Every haematological parameter was still within normal limits. The nutritional content of SS was increased through biodegradation using P. ostreatus, and adding 15% BSS to goat diets improved nutrient intake and preserved health, providing a sustainable, unconventional feed substitute. In summary, adding BSS to goats' diets was judged safe because it promoted peak performance.

Blood metabolic profiles have been used to diagnose and predict the course of animal diseases. They can also be used to evaluate the wellbeing of animals or determine whether dietary changes have an impact on their physiology [54,55]. An assessment of an animal's blood profile may provide some information about the possibility of a nutritional intervention to address the animal's metabolic and health requirements [56–58]. The blood metabolic profile can help determine the welfare status of the animals, especially when it comes to their health and nutrition.

In order to investigate how ruminants react to fungus-treated agro-industrial by-products or crop residues, Ochepo et al. [59] fed West African dwarf sheep four gradated levels of fungal-degraded cassava peel diets with 8%, 16%, 24%, and 32% inclusion, as well as a control diet that contained 32% untreated cassava peels. According to the results of the blood samples that were taken, the packed cell volume values (26.47–39.23%) were largely within the sheep's typical range (27–43%). The values for the red blood cell count (RBC) (8.68–13.78 x1012/L) were comparable to the typical range for sheep (9–14 x106/uL). The study's total protein values, which ranged from 62.33 to 75.77 g/L, were comparable to the typical range of 60 to 75 g/L for sheep. Compared to the typical range of 22 to 30 g/L stated for sheep, the albumin values (30.67 to 48.60 g/L) found in this investigation were higher. Additionally, they found no discernible variations in the levels of white blood cells, packed cell volume (PCV), haemoglobin (HB), red blood cells (RBC), and their indices mean corpuscular volume (MCV), mean corpuscular haemoglobin (MCH), and mean corpuscular haemoglobin concentration (MCHC) among the treatments. Comparing the 8% and 16% fungal-degraded cassava peels to the control and other dietary regimens, the platelets were noticeably greater. In comparison to the other treatments, treatment 24% had significantly greater levels of neutrophils, eosinophils, monocytes, creatinine, and albumin. The experimental animals' health status was shown to be unaffected by the addition of fungal-degraded cassava peels (FDCP) to their diet. They came to the conclusion that giving FDCP to nursing WAD sheep is safe. Goats were given experimental diets including 0, 20, 30, and 40% fungus-treated cassava waste-based diets for 56 days in a related study conducted by Belewu et al. [60]. Animals fed the studied food had their blood parameters (PCV, HB, RBC, and WBC) compared to those fed the control diet. These findings suggest that adding Trichoderma-treated cassava waste to goats' diets did not negatively impact the animals' overall health or haematological indicators. On the other hand, Belewu et al. [61] fed goats diet A (control), diet B (50 percent soybean cake and 50 percent Jatropha curcas kernel cake treated by Rhizopus oligosporus), diet C (50 percent Rhizopus nigricans treated Jatropha curcas kernel cake and 50 percent Soybean cake), diet D (100 percent Rhizopus oligosporus treated Jatropha curcas kernel cake), and diet E (100 percent Rhizopus nigricans treated Jatropha curcas. Diet B, which contained 50% soybean cake and 50% Jatropha curcas kernel cake treated with Rhizopus oligosporus, showed promise because neither the animals on this diet nor the control showed any signs of death. Furthermore, the blood of animals fed diet B had comparable levels of PCV, RBC, HB, and neutrophils to those fed diet A. It was determined that growing goats could be fed a diet that included 50% soybean cake and 50% Jatropha curcas kernel cake treated with Rhizopus oligosporus.

A control ration consisting of 57% concentrate feed mixture, 19% clover hay, and 24% untreated rice straw (URS) was given to three groups of rams by El-Bordeny et al. [62].

Groups two and three were given rations that contained treated rice straw with Trichoderma reesei and Trichoderma viride in place of URS, respectively. Total plasma protein and albu-min concentrations in the treatment groups were not significantly higher than those in the control group, according to the serum biochemical data. This result is consistent with that of Ochepo et al. [59], who found no significant variation in total protein between the dietary regimens. Research on turning biodegraded wheat straw into nutrient-dense cattle feed was reviewed by Anaso [11]. The calves were fed four different diets: T1 control (wheat straw and concentrate mixture), T2 (5-day Biotech Feed and concentrate combination), T3 (5-day Biotech feed and 50% grain replaced from concentrate mixture), and T4 (5-day Biotech Feed and 100% grain replaced from concentrate mixture). The results of the blood biochemical examination were consistent with previous research and revealed non-significant variations in PCV, HB, total protein, albumin, and serum creatinine [59,60,62].

### *3.5. Factors Affecting Semen Characteristics, Scrotal Morphology and Morphometric Parameters of Ruminants*

Infertility is a major constraint in livestock production, with males contributing about 30% of cases. In small ruminants, male fertility is particularly crucial since one buck often services multiple does. Factors that disrupt spermatogenesis, reduce sperm production and quality, or compromise libido negatively affect herd fertility and profitability [63,64]. Among these factors, nutrition plays a central role. Dietary deficiencies or imbalances in energy and protein can impair spermatogenesis and hormone synthesis, while improved nutrition enhances testicular development, semen production, and overall reproductive performance [65].

The use of agro-industrial by-products (AIBPs) and crop residues offers an economical way to meet nutrient requirements in goat production systems, particularly in Nigeria where feed costs are high and conventional feed ingredients are scarce. Various studies have demonstrated that ruminant spermatogenesis and semen quality are responsive to improved dietary protein and energy levels, often achieved through strategic inclusion of AIBPs in diets [10]. For instance, biodegraded sugarcane scrapings (BSS) included at 15% of the total diet improved semen volume, scrotal length and circumference, and final body weight in bucks compared to 0% and 30% inclusion levels, without adverse effects on sperm motility or viability [3]. Testosterone levels and libido were also optimized at moderate BSS inclusion.

Similarly, Kheradmand et al. [66] found that rams fed diets supplying energy and protein above maintenance (e.g., higher levels of barley and soybean meal) had significantly larger scrotal size and increased sperm concentration. Ososanyo et al. [67] demonstrated that blending cassava peel silage (CPS) with pineapple waste (PW) up to 60% of the diet did not negatively affect scrotal circumference, sperm motility, or viability in rams. Likewise, Belewu et al. [60] showed that Trichoderma-treated cassava waste (TTCW) at 40% improved fertility, fecundity, and prolificacy rates in West African Dwarf does compared to lower inclusion levels.

These findings emphasize that AIBPs, when properly processed and balanced with other feed components, can support or even enhance reproductive performance. Improved nutrition from locally available by-products increases seminiferous tubule development, testicular mass, sperm output, and semen quality [68–70]. Scrotal circumference and semen traits are key indicators of breeding soundness and are positively correlated with reproductive success [64,71]. Thus, incorporating AIBPs like sugarcane scrapings, cassava peels, and fruit-processing residues provides a cost-effective strategy to improve buck fertility and doe reproductive outcomes.

While environmental factors such as temperature and photoperiod affect reproduction [72], good plane of nutrition using unconventional feedstuffs buffers these effects, maintaining semen quality year-round. Hence, a functional breeding soundness evaluation program should integrate body condition, testicular traits, and semen analysis, alongside a feeding program that leverages affordable, nutrient-rich agro-industrial by-products.

*3.6. Effect of Feeding Biodegraded Agricultural Wastes on Body Thermoregulatory Parameters of Ruminants*

According to Anaso and Alagbe [73], there is sufficient evidence that elevated ambient temperatures negatively influence livestock performance by reducing feed intake, nutrient utilization, and metabolic efficiency. Heat stress challenges the thermoregulatory capacity of goats, affecting their productivity and welfare. Thus, feeding strategies that combine adequate nutrient supply with cost-effective feed resources are crucial, particularly in tropical and subtropical regions.

One promising approach is the inclusion of agro-industrial by-products (AIBPs) such as sugarcane scrapings, cassava peels, and other crop residues, which provide affordable energy and protein sources. Olafadehan et al. [15] demonstrated that Pleurotus ostreatus-biodegraded sugarcane scrapings (BSS) can be included in goat diets up to 30% without adversely affecting body thermoregulation, metabolic welfare, or health. The biodegradation process improves fiber digestibility and nutrient availability, allowing goats to maintain physiological stability even under heat-challenged conditions.

Similarly, Kusuma et al. [74] studied varying protein levels (13%, 16%, and 19% CP) in goat diets and found that rectal temperature and respiratory rate were not significantly affected ($P>0.05$), though heart rate increased with higher protein supplementation. These findings suggest that diets balanced with adequate protein, potentially sourced from unconventional feed ingredients like agro-industrial residues, support physiological resilience without exacerbating heat load.

The effects of Piliostigma thonningii seed essential oil (Milne-Rech seed essential oil, MSEO), also referred to as camel's foot essential oil, and biodegraded sugarcane scrappings on thermoregulation, immune and oxidative stress responses, serum biochemical indices, and reproductive traits in growing sheep were examined by Anaso et al. [75] and Anaso [76]. In a fully randomized design, twenty-one healthy Yankassa ram lambs (6–7 months old; average body weight: 10.55 ± 0.60 kg) were divided into three food regimens at random. For 16 weeks, each animal was given a standard basal diet supplemented with 0 mL/kg of MSEO (T1-control), 5 mL/kg (T2), or 10 mL/kg (T3). T1 had considerably higher ($P < 0.05$) rectal temperatures than T2 and T3, which were statistically similar ($P > 0.05$). The rectal temperatures ranged from 38.93 °C to 39.95 °C. Treatment had no discernible effect on respiratory rate (23.29–23.91 cycles/min), heart rate (83.43–83.54 bpm), or earlobe temperature ($P > 0.05$). The findings suggest that dietary interventions particularly the addition of nutrient-rich agro-industrial by-products (AIBPs) and essential oils can alleviate the unfavorable impacts of heat stress on metabolic efficiency, immunological function, and overall productivity in small ruminants.

## 4. Conclusions

As this review has demonstrated, crop residues and agro-industrial by-products are essentially inexpensive feed alternatives that, with the right processing and supplementation, can maintain or even enhance the nutritional value, physiological health, and reproductive performance of small ruminants.

Additionally, the addition of biologically treated components, such as fermentative microorganisms and Pleurotus ostreatus-biodegraded substrates, shows encouraging promise in enhancing nutrient availability and digestibility. Appropriate processing techniques can lessen the limits posed by nutrient variability and anti-nutritional variables. All things considered, in small ruminant farming systems, the thoughtful application of these alternative feed resources provides a viable solution to lower production costs, enhance animal performance, and lessen environmental impact.

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