

Review

Not peer-reviewed version

Advancements in Sustainable Livestock Feed: Harnessing Drought-Tolerant Crops

[Sipho Tonisi](#), [Tafadzwa Kaseke](#)*, [Ngobile Masondo](#), Jerry O. Adeyemi, [Olaniji A. Fawole](#)*

Posted Date: 26 January 2026

doi: 10.20944/preprints202601.1894.v1

Keywords: climate smart agriculture; climate change; alternative livestock feed; drought resilient crops; *Opuntia ficus-indica*



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a [Creative Commons CC BY 4.0 license](#), which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Review

Advancements in Sustainable Livestock Feed: Harnessing Drought-Tolerant Crops

Sipho Tonisi ^{1,2}, Tafadzwa Kaseke ^{1,2}, Nqobile Masondo ³, Jerry O. Adeyemi ^{1,2} and Olaniyi A. Fawole ^{1,2,*}

¹ Postharvest and Agroprocessing Research Centre, Department of Botany and Plant Biotechnology, University of Johannesburg, P.O. Box 524, Auckland Park, Johannesburg, 2006, South Africa

² South African Research Chairs Initiative in Sustainable Preservation and Agroprocessing Research, Faculty of Science, University of Johannesburg, P.O. Box 524, Auckland Park, Johannesburg, 2006, South Africa

³ Agricultural Research Council-Vegetables, Industrial and Medicinal Plants, Roodeplaat, Pretoria, South Africa

* Correspondence: olaniyif@uj.ac.za

Abstract

Livestock feed shortage is a serious global problem, worsened by climate change-induced droughts that continue to disrupt its production, consequently threatening food and nutrition security. Drought poses a significant threat to conventionally farmed feed crops, such as maize and soybeans, reducing their availability and negatively impacting the livestock industry. These crops cannot withstand intense drought, creating a need for alternative feed sources with good nutritional value, positive health benefits and livestock performance, as well as cost reduction potential for farmers. Research continues to explore drought-resistant crops such as sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), cassava (*Manihot esculenta*), false banana (*Ensete ventricosum*), and cactus pear (*Opuntia ficus-indica*) for use as traditional feed substitutes or in hybrid feedstock production to enhance food security, support farmers, and conserve the environment. Unlike the conventional feed crops, these underutilized crops are resilient to arid conditions, use less water, and possess higher nutritional value, making them crucial for climate change adaptation and sustainable agricultural systems. Despite the growing recognition of drought resistant crops in livestock feed systems, a comprehensive review discussing the advancements and potential of drought-resistant crops as livestock feed is lacking in literature. Therefore, this review discusses the critical role of selected key drought-resilient crops as alternative livestock feed, covering the drivers for their use, utilization and processing studies, quality-determinants, associated challenges, and sustainable innovation strategies to inform policy making.

Keywords: climate smart agriculture; climate change; alternative livestock feed; drought resilient crops; *Opuntia ficus-indica*

1. Introduction

Climate change has brought devastating impact on agricultural activities that are central to humanity. Climate variability, such as unusual rainfall patterns and rising temperatures, negatively impact both food and livestock feed crops, leading to food and nutrition insecurity for both human and livestock [1]. Such developments have spurred research on alternative and sustainable livestock feed sources, with a focus on underutilized plants. The goal of this approach is to identify options that are simultaneously climate-resilient and nutritious for domesticated livestock. The selection of alternative feeds is intended to supplement existing feed sources during periods of shortage, while still ensuring optimal livestock performance parameters and improved profit margins for farmers. Livestock such as cattle, sheep, pigs, and chickens are economically crucial, providing nutritious food, income, and wealth significantly improving food and livelihoods of the citizens [2,3]. Therefore,

solutions that support sustainable livestock production and alleviate the impact of feed shortages due to climate change are warranted.

The conventional livestock feed sources are not sufficient to mitigate feed shortages as their use and availability are further restricted by factors such as land and water use conflicts, feed cost inflations, and the continuous competition between humans and livestock for food sources [4]. The term “conventional feed” in this review covers a range of feedstuff that may differ depending on the region and farming system. Common, conventional feed sources include but are not limited to; forages (grasses and fodder), grains, oilseeds, soybean and sunflower [5]. Feed deficits, primarily due to the impact of climate change on these conventional feed sources, have resulted in the emergence of alternative sources of livestock feed including a wide range of products produced from drought-resilient crops, insects, tree leaves, agro-industrial fruit and vegetable wastes [6,7]. Among these different feed sources, drought-resilient crops are considered a more sustainable option, due to their availability during dry seasons, superior nutritional content, and suitability for small-scale farming systems [8,9].

The eco-friendly nature, biomass abundance, and affordability of drought resistant crops further enhance their appeal, particularly for small- to medium-scale livestock production businesses, especially in arid and semi-arid regions. Despite the highlighted benefits for livestock farming, drought resistant crops have been largely overlooked and underutilized as sustainable feed sources, limiting their usage during drought [10]. Limited utilization of drought resilient crops stems from limited available research that focuses on their inclusion in feed rations which can be an opportunity to provide farmers and feed industries with information that can help increase their options for feed alternative sources. Currently, in order to supplement livestock' diets, farmers resort to importing feed, which is often more expensive and leads to unsustainable livestock production, especially those of small-medium status. Thus, addressing this important research gap is crucial, given the increasing prevalence of drought and the need for resilient and cost-effective livestock feed options.

Literature has highlighted the potential of several drought-resilient crops—sorghum (*Sorghum bicolor* (L.) Moench), pearl and finger millets (*Pennisetum glaucum* (L.) R. Br and *Eleusine coracana* (L.) Gaertn), cassava (*Manihot esculenta* Crantz), false banana (*Ensete ventricosum* (Welw.) Cheesman), and cactus pear (*Opuntia ficus-indica* (L.) Mill)—as sustainable alternatives for feed sources [11–15]. Findings from the above-mentioned studies demonstrate the need to consider drought resilient crops as valuable resources to support food and nutrition, food security and climate smart adaptation. However, the optimal quality of the feed from drought resistant crops warrants careful consideration of processing techniques, pre-harvest factors, and maturity stages. These factors interact to determine the nutritional value, digestibility, and overall suitability of the crops for livestock feed, providing critical information required by livestock feed processors. However, studies analyzing the synergistic effects on the quality of the feedstock are still limited.

This review critically discusses the role of key drought-resilient crops as alternative livestock feed, highlighting the main drivers such as crop usage, processing and application to improve livestock health. Furthermore, factors influencing their quality, challenges, and strategies to promote crop innovation as climate smart agriculture strategy is highlighted.

2. Main Drivers to the Use of Drought-Resilient Crops as Livestock Feed

The primary drivers for the increased use of drought-resilient crops as alternative livestock feed include the impacts of climate change, particularly the effect of drought on conventional feed sources, and the need for sustainable food production systems. Farmers are faced with reduced crop yields and quality due to extreme drought, leading to livestock feed shortages and increased costs of livestock production. Water scarcity and the rise in temperature have heavily impacted the production of conventional livestock feed sources resulting in a decline in livestock performance and productivity [16]. Various studies have reported on the negative effects of drought on livestock farming across the globe. For instance, Klinck et al. [17] reported a decline in forage and livestock production among small holder and semicommercial farmers in South Africa. Severe drought in the

semi-arid regions of Ethiopia between 1985 and 2011 resulted in significant livestock deaths due to water and feed shortages [18]. In addition, Puerto Rico faced a severe drought that significantly hindered the growth of fodder and grasses, negatively affecting livestock production and farmers' livelihoods [19].

Another example of a severe drought occurrence that caused undesired outcomes on livestock production is the 2015-2016 El Niño phenomenon which significantly impacted global crop and livestock productivity, with notable effects in regions like Southern African, South and Central American states [20–23]. This drought led to a drastic decline (8-78%) in maize production in Southern African nations such as Zambia, South Africa, Zimbabwe and Namibia (Figure 1A). In South and Central American countries like Bolivia, Brazil, Honduras, El Salvador, and Nicaragua, the drought resulted in 31-60% decrease in maize production (Figure 1B). The consequence of the El Niño drought significantly increased the prices of stockfeed, meat and other livestock products, impacting both farmers and consumers. Evidence from other drought related studies reported a 20-25% decrease of maize production in Thailand between 2019-2020, a 25.8% decline in livestock holdings and 8.4% decrease in milk production in Ethiopia, as well as reduced the nutritional value of crops like wheat, maize, and alfalfa [24]. Thus, beyond crop reduction, droughts cause serious disturbances to diets, with a significant depletion in protein content consumption. These factors highlight the far-reaching consequences of drought on food security and livelihoods. Faced with the highlighted challenges, integrating drought-resilient crops into livestock feeding is crucial for sustainable agriculture, especially for livestock productivity. However, understanding the mechanisms behind drought resilience and categorizing crops based on their drought response is essential for their effective utilization as stockfeed resources.

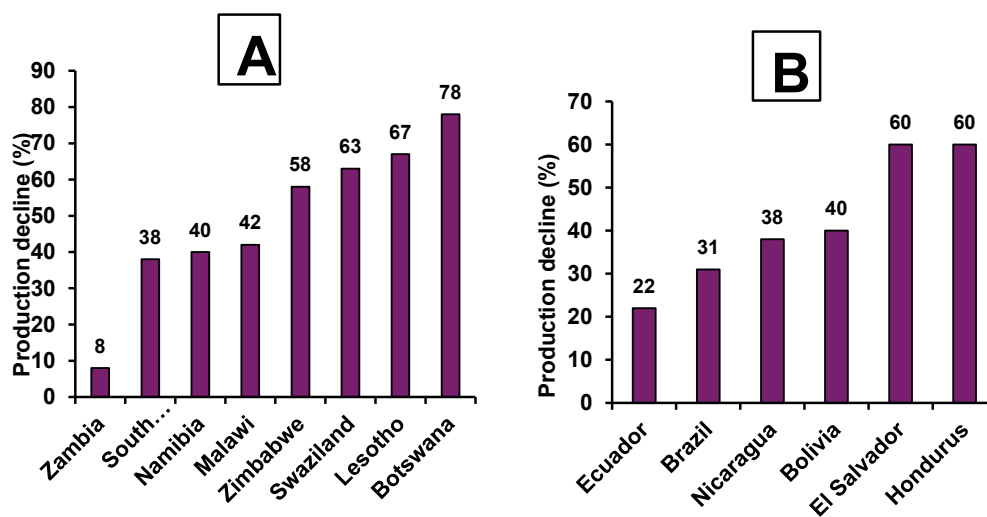


Figure 1. Maize production decline due to El Niño drought (2015-2016) in (a) Southern African, and (b) Central and South American countries. Data sources: [1], [2], [3] and [4].

3. Classification of Drought Resistant Crops

The primary factor in categorizing crop varieties into drought-resilient classes is their ability to withstand different types and intensities of drought, coupled with their mechanism of action that enables them to execute such abilities. This classification aims to facilitate the selection of appropriate crops for sustainable agriculture, ensuring that the chosen varieties can thrive under the conditions in which they can be grown under. Although drought resilient ability of plants is a multifarious mechanism, literature has been able to summarize it into four broad categories- (i) drought avoidance, (ii) drought escape, (iii) drought tolerance and (iv) drought recovery. These classifications

are derived from varying morphological, physiological and biochemical adjustments plants express to mitigate unwanted impacts caused by drought occurrences [25,26]. The drought resilience mechanism involves varying degrees of photosynthetic pathways, water use potential, antioxidant systems, regulation of hormones, leaf and root traits [27]. The previously noted categories are briefly explained as follows:

(i) Drought avoidance: Drought avoidance crops work by keeping water potential elevated at cellular levels enabling them to survive and function even with limited water availability [28]. This is achieved through a combination of drought avoidance and drought tolerance strategies.

(ii) Drought escape: These types of crops are known for rapid flowering which allows the completion of their life cycle before drought conditions become severe [27]. During this period, rapid plant organ development can be achieved due to high rates of metabolic processes that lead to efficient cellular growth and mitosis [29]. In addition to rapid flowering, these plants express early maturity and high photosynthetic rates [30].

(iii) Drought tolerance and recovery: These crops can withstand and survive in conditions of low water availability while maintaining the physiological processes necessary for growth and productivity [30,31]. This allows for the cultivation of drought-resistant crops in arid and semi-arid regions. These plants utilize various mechanisms to cope with water stress, ensuring survival and enabling economic viability.

From studying these various drought resilience mechanisms, certain plants have been reported to exhibit an outstanding recovery ability after experiencing severe drought [25]. It must be noted that drought occurrence and plant response mechanisms are a complex dynamic concept yet to be extensively researched. It has been reported that some plant species are able to execute integrated response mechanisms, signaling a broader adaptability during different drought intensities [25]. As such, the underlying mechanisms respective to each drought response strategy have been studied. Out of those varying biological processes, plants with phenomenal photosynthetic pathways have emerged as the next species for sustainable agricultural crop production. Therefore, the proceeding section discusses the types of drought tolerant crops with efficient photosynthetic pathways and their mechanisms of action against drought.

3.1. Types of Drought Tolerant Crops and Their Mechanisms of Action

Drought-tolerant crops are characterized by effective photosynthetic mechanisms that allow them to thrive in dry and hot conditions. Their ability to concentrate and fix carbon through the conversion of atmospheric inorganic carbon dioxide (CO₂) into essential organic compounds has been implicated in crop resilience against drought stress [25]. Based on the carbon fixation and water use efficiency (WUE) pathways, these crops are grouped into 3 distinct classes: C₃, C₄ and crassulacean acid metabolism (CAM) plants [32]. Although these three classes possess similar metabolites, such as malate and pyruvate, their carbon fixation efficiency varies, influencing their level of drought tolerance. Specifically, CAM plants possess the highest drought tolerance, when compared to C₃ and C₄ plant species [33]. Meanwhile, C₃ plants are generally considered to be least tolerant than C₄ [34]. Thus, C₃ plants can be considered less suitable for extremely drought-prone environments. Therefore, this review will concentrate on C₄ and CAM plants, exploring their unique drought tolerance mechanisms and potential use as alternative livestock feedstock in agricultural systems.

3.1.1. Drought-Tolerant Crops Utilizing The C₄ Photosynthetic Pathway

The C₄ plants such as sorghum are highly recommended for livestock farmers in arid and warm climates due to their superior drought resistance strength [35,36]. These plants convert atmospheric CO₂ into malate or malic acid—a four-carbon compound—in the mesophyll cell, hence the name C₄, and transfer it into bundle sheath cell for decarboxylation (Figure 2). In addition to this exceptional photosynthetic pathway, their ability to thrive in drought-stricken environments has been attributed to reduced interaction and reaction with oxygen molecules, as it leads to unwanted photorespiration, an inefficient process that can result in energy and water loss [37]. Therefore, the significance of C₄

drought-tolerant plants as alternative feed sources lies in their extended availability during dry seasons, making them crucial for mitigating feed shortages, particularly among smallholder farmers in arid regions and developing states. Additionally, their efficient water and nitrogen utilization enhances their suitability for pasture production [38]. Compared to C_3 plants, the C_4 pathway possesses a higher energy conversion efficiency, which enables them to optimize solar radiation for the production of essential biochemical compounds [38]. This high energy conversion capacity translates into increased carbohydrate content, which is crucial for maintaining livestock metabolism and overall productivity. Additionally, the C_4 pathway enables these plants to execute photosynthesis even during low CO_2 concentration, and the presence of ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco), as illustrated in Figure 2. This allows for efficient use of nitrogen [39], as nitrogen is a vital element needed in plant growth, protein build up, nucleic acid, amongst many other benefits. Some of the commonly used livestock feed belonging to C_4 crops include some variety of maize, and millets [40]. These crops not only serve as primary feed sources but also complement the existing feed formulations in livestock production systems, further enhancing their utility in sustainable livestock nutrition [41].

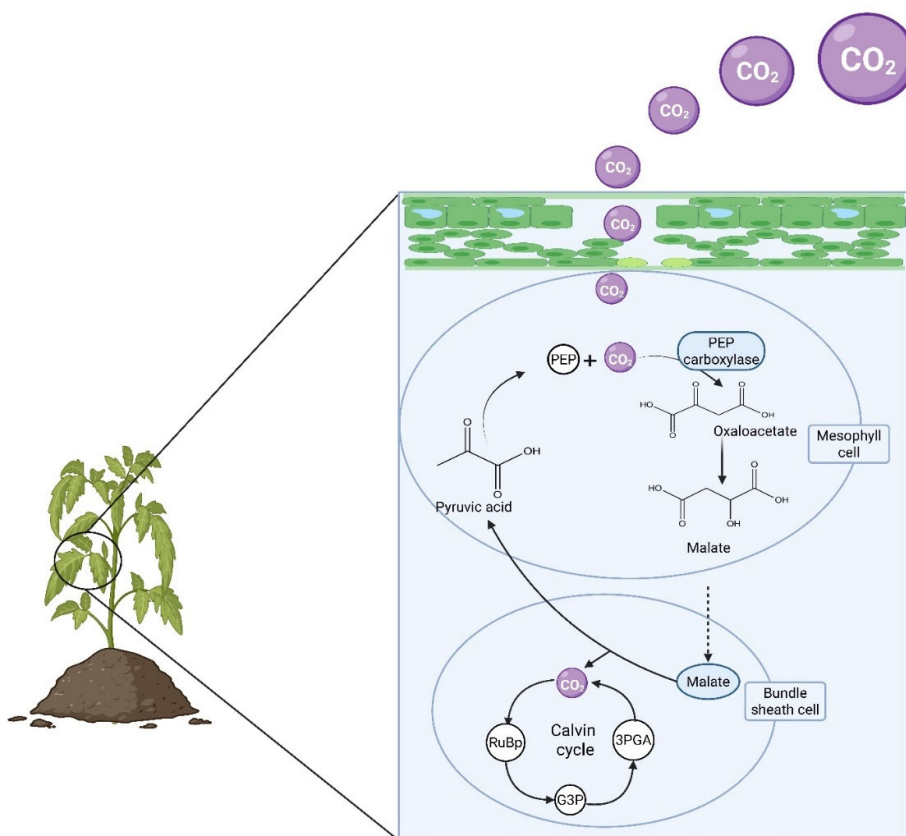


Figure 2. C_4 photosynthesis pathway of drought tolerant crops. Adapted from Langdale [5]. Created using BioRender.

3.1.2. CAM Drought-Tolerant Plants

Even though CAM and C_4 plants share similarities in their carbon fixation processes, CAM plants stand out because of their superior water conservation properties and their ability to completely prevent wasteful photorespiration [43]. Hence, through evolutionary adaptation, CAM plants have developed an efficient survival mechanism that enables them to thrive in extremely arid environments [33]. Their photosynthetic pathway operates through two primary processes:

acidification at night and deacidification during the day, as illustrated in Figure 3. This unique mechanism allows CAM plants to open their stomata at night to absorb CO_2 while reducing water loss, making them highly efficient in moisture retention. Acidification occurs by fixing CO_2 when reacting with phosphoenol pyruvate (PEP); a process catalyzed by PEP carboxylase to form oxalo acetic acid (OAA). OAA is converted to malic acid that is later stored in vacuoles. During the day, the stored malic acid is converted to pyruvate that is transported to the mitochondria where it is catalyzed to OAA, by pyruvate carboxylase. OAA will enter the Krebs cycle to generate energy for the needs of the plant. It is worth noting that the stomata open at night and closes during the day.

Their water-use efficiency is further enhanced by root hydraulic conductivity, which, under wet soil conditions, can be up to six times higher than in other plant species [44]. These types of plants include *Opuntia ficus-indica*, *Ananas comosus* (pineapple), and Agave species which have gained industrial and agricultural significance in the recent years [45–47]. While these crops may have lower protein content than conventional feed sources, they are rich in vitamins, carbohydrates, and essential minerals, making them valuable in producing hybrid feeds [47]. Gusha et al. [48] report that CAM plants contain five times higher dry matter (DM) than other plants, which enhances their suitability as livestock feed. The Food and Agricultural Organization (FAO) associated publication recognizes and promotes CAM plants like *Opuntia ficus-indica* as valuable resources for nutritional properties and recommends their integration into livestock feeding systems as a sustainable alternative feed source during droughts and dry seasons [49,50]. This demonstrates how underutilized plants have garnered support across the globe and their potential to revolutionize the livestock feeding systems.

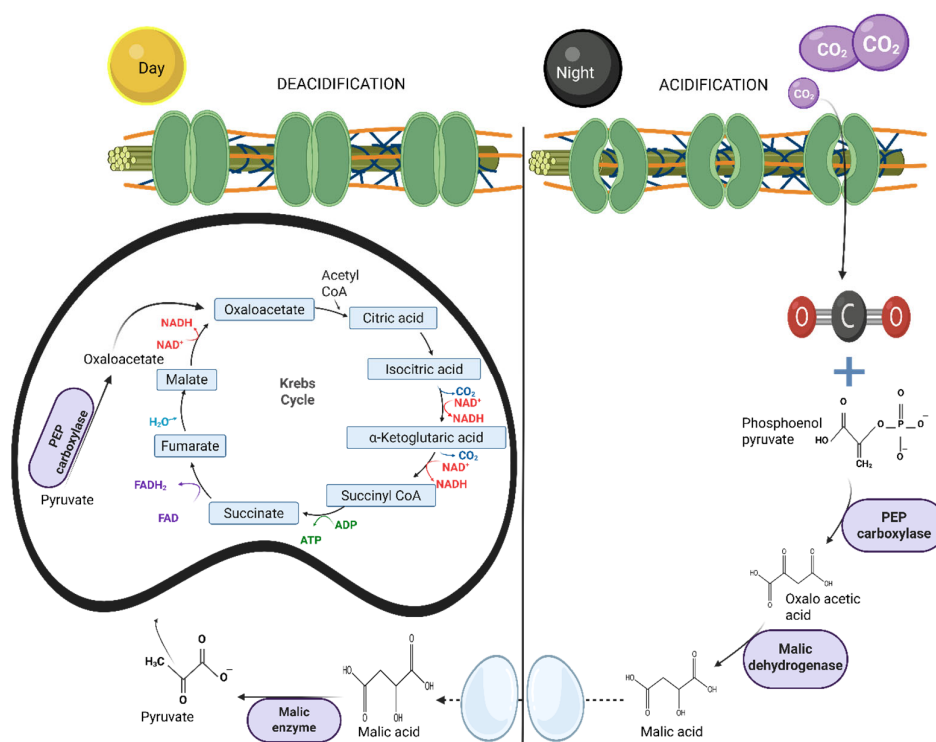


Figure 3. CAM photosynthetic pathway in drought tolerant crops. Adapted from Yamori et al. [6]. Created in BioRender.

4. Recent Studies on The Utilization of Key Drought-Tolerant Crops in Livestock Feeding Systems

Several drought-tolerant crops are crucial in livestock feeding systems, particularly in arid and semi-arid regions. Sorghum (*Sorghum bicolor*), millets (*Pennisetum glaucum* and *Eleusine coracana*), false

banana (*Ensete ventricosum*), and cactus pear (*Opuntia*) are notable examples, discussed in this section. The effect of processing on these crops and impact of the processed product on livestock nutrition and health is also discussed.

4.1. *Sorghum Bicolor* (L.) Moench

Sorghum (*Sorghum bicolor*) (Figure 4A) is a prominent drought-tolerant crop, recognized as the most widely cultivated crop for livestock and ranked fifth globally in production, with approximately 65 million tons produced annually [52]. This crop grows well in arid regions of different continents with Nigeria, Zimbabwe, India, China, United States, Mexico, Sudan, Ethiopia, Brazil, Argentina and Australia ranked as the top producers [53]. Besides its' drought tolerant strength, sorghum is further appreciated for its rich nutritional composition, containing 9.5-10.4% protein, 1.5% fat, and 6.8% ash, which makes it a better alternative to other feed sources [15,54]. In addition, sorghum is a shorter seasonal crop, and its various parts (leaves, straws, and byproducts) are valuable as supplemental sources for livestock feed rations [54]. As shown in Table 1, various studies have demonstrated the potential of using different parts of sorghum, for livestock feed applications. Yusriani et al. [54] reported that using the ensilage technique can assist in extending the postharvest lifespan of sorghum leaves and stems which showed a positive response in livestock feed applications. Within the same study, sorghum grains were seen as a beneficial addition to chicken feed, potentially increasing survival rates at a 30% inclusion level compared to a control group.

Sweet sorghum (12%) produced higher villus heights on the intestinal compartments' duodenum, ileum and jejunum of male geese [55]. Villus heights of the intestines are key indicators linked to nutrient absorption, as such, the greater the height, the more efficient the nutrient absorption process becomes, which signifies the quality of the feed produced [56]. Sorghum was also used to replace maize in broiler diets where positive results relating to feed intake, feed conversion and live weight gain during the early days of rearing were observed. The tested inclusion rates were noted to increase weight gains between day 21-48 [15]. In addition, the incorporation of sorghum in broiler feed at 30% increased broiler survival rates up to 95.6% compared to the control diet that produced 93.3%. With a similar approach of replacing maize with sorghum, Pontieri et al. [14] demonstrated that sorghum is a viable option for lactating cows and does not compromise livestock performance. High production of compounds such as succinic acid, 2-ethylacrylic acid and glutamic acid were observed during lactation in cows fed with sorghum diets [15,57]. These chemical compounds positively contribute to the quality and flavor of milk products. Besides the nutritional and health benefits, the inclusion of sorghum in livestock is related to its lower costs of production [14]. All these factors put together make sorghum a viable and sustainable crop for livestock feed. Additional studies demonstrating the potential of sorghum as livestock feed are presented in Table 1.

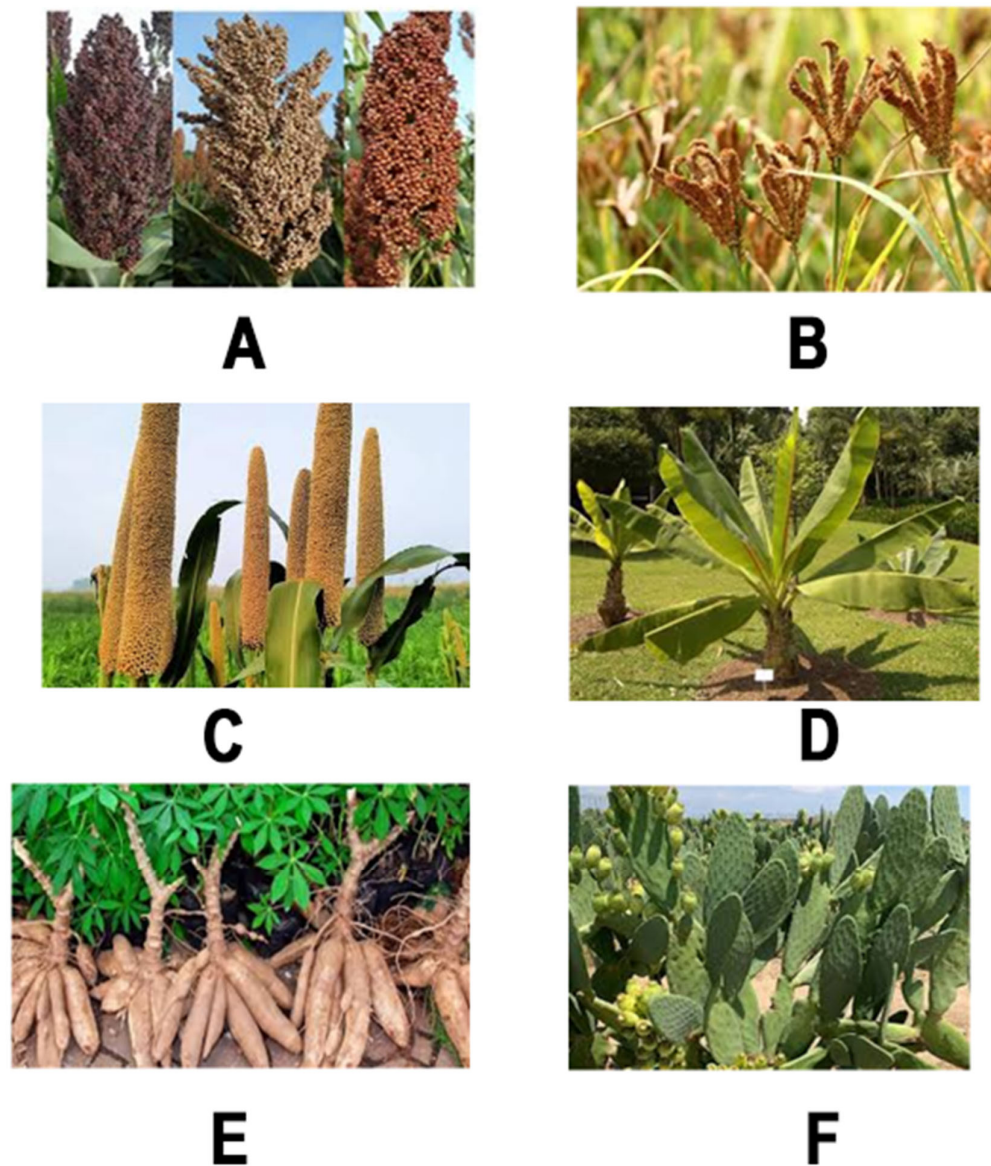


Figure 4. Drought tolerant crops; (A) sorghum (*Sorghum bicolor*), (B) finger millet (*Eleusine coracana*), (C) pearl millet (*Pennisetum glaucum*), (D) false banana (*Ensete ventricosum*), (E) Cassava (*Manihot esculenta*) and (F) cactus pear (*Opuntia ficus-indica*). .

4.2. *Pennisetum Glaucum* (L.) R. Br and *Eleusine Coracana* (L.) Gaertn

Pearl and finger millets (*Pennisetum glaucum* and *Eleusine coracana*) have been extensively studied as drought-tolerant forages, with various species demonstrating significant utility in livestock feed applications. Their application in the feed industry is attributed to the presence of desirable nutritional properties and bioactive constituents, which renders them ideal for inclusion in feed formulations [58]. For instance, a comparative analysis study by Gowda et al. [59] revealed that finger millet straw contains elevated levels of CP and various minerals, including phosphorus, calcium, copper, and magnesium, better than conventional rice straws. Several millet varieties are documented for livestock feed, with *Eleusine coracana* and *Pennisetum glaucum* being the most researched (Figure 4B and 4C), while millet husks, a byproduct of millet processing, are also less studied [60,61]. These two types are recognized as the predominant groups within the millet category, as they account for a substantial proportion of millet production and trade [58]. Mugula et al. [62] established that *Pennisetum glaucum* grains could fully replace maize in the diets of confined cattle, leading to

increased DM digestibility and nutrient availability for grazing beef cattle during the dry season. Replacement of corn with various levels of *Pennisetum glaucum* resulted in an increased weight gain when fed to broilers [63].

A comparative evaluation between milled and grain diets made from a Gayamba *Pennisetum glaucum* showed that whole grains performed better than milled grains, when fed to chickens for 49 days [64]. During the finisher phase, dry feed intake of the treatment that contained 15% whole grain millet increased to 118.77 g compared with 45.18 g recorded during the starter feeding stage. This result is indicative of the adaptability whole grain pearl millet offers to broiler diets. The increase in dry feed intake was also linked to the increase in daily weight gain as well as feed conversion ratio (FCR). In another study, Oskey [65] demonstrated that Brown Midrib (BMR) pearl millet was preferred over conventional pearl millet when evaluating various nutritional parameters, including neutral detergent fiber (NDF), CP, sugars, and in vitro NDF digestibility. Among these parameters, BMR pearl millet exhibited superior performance in terms of in vitro NDF digestibility, achieving 66.3% compared to 63.6% from conventional pearl millet [65]. These results suggest high fiber in BMR pearl millet which was fermented by rumen gut microbiota into respective health beneficial byproducts. Using various inclusion levels, millet forms and enzyme addition in pearl millet-based diet, it was observed that 100% ground pearl millet diet resulted in increased intestinal weight of Japanese quails [66]. This was attributed to increased intestinal morphology due to enhanced functional nutrient absorption and digestion processes in the tested birds. In addition, high contents of fiber can also widen intestinal muscles to allow efficient breakdown of the fibrous components [66]. Other studies demonstrating the beneficial inclusion of pearl millet in livestock treatments with a focus on nutritional value, performance parameters, carcass and histological traits are presented on Table 1.

According to Gowda et al. [59] feeding finger millet straw to dairy cows resulted in a higher average daily milk yield (7.0 liters) compared to feeding rice straw (6.3 liters), enhanced digestibility of CP, DM, acid detergent fiber (ADF) and NDF. This indicates a potential benefit of finger millet for increasing milk production in cattle and nutrient metabolism. However, the same study found that incorporating finger millet into sheep diets negatively impacted digestibility coefficients including DM, organic matter (OM), total digestible nutrients and total carbohydrates. This implies that the effect of finger millet may vary depending on the livestock species and its digestive system [67]. Nonetheless, finger millet is still recognized for its high nutritional value, boasting rich protein content and essential minerals like zinc (Zn) [68].

Other studies evaluated various forms of finger millet-based diets for Mandya lambs, Sahelia goats and cattle [60,61,69]. Performance indices revealed high CP intake of 66% g per day, from the extruded finger millet-based diet, compared to those made from area sheath and maize cob with values of 56.91% and 60.31% g per day, respectively, when offered to Mandya lambs [61]. Varying proportions of finger millet in silage production proved that the inclusion of 44% finger millet produced reliable results with regards to milk quality and production [60]. According to Tong et al. [69] feeding cattle with millet straw combined with maize showed an increase in fungal population of *Basidiomycota* compared to those fed with corn only. The existence of this rumen fungi in sufficient amounts is associated with an enhanced ability to degrade fiber within the ruminant digestive systems [69].

4.3. *Ensete Ventricosum* (Welw.) Cheesman

False banana (*Ensete ventricosum*) (Figure 4D), particularly found in Ethiopia is a drought-tolerant crop used as a feed component for lactating livestock, especially during dry seasons. However, there is a lack of extensive research supporting its widespread use as livestock feed beyond Ethiopia and exploring its full impact on livestock health and farming systems. In spite of this, *Ensete ventricosum* exhibits characteristics suitable for livestock feed due to its high-water content (85-90%), elevated amino acid levels, protein content of 13%, crude fiber (20%), and sugar content of 10% suggesting that it can be used as fodder or silage [8]. Fiber and stalks obtained from false banana

showed considerable amounts of protein, mineral composition (K and Fe) supporting its suitability as a fodder crop [70]. Fekade [71] studied the impact of feeding white leghorn layers and broilers with different rations of *Ensete ventricosum* replacing maize at varying proportions (Table 1). The study revealed that a 30% maize replacement provided more energy for the chickens leading to increased egg production and profit margins. In another study, various treatments including wheat bran and *Ensete ventricosum* were offered to Doyogena sheep in a randomized complete design approach and parameters such as feed intake, body weight change, feed conversion efficiency, digestibility and chemical composition were investigated. Notably, treatments that contained higher contents of *Ensete ventricosum* produced higher intake of ME and in vitro organic DM [24]. Given these promising findings, further studies on the use of *Ensete ventricosum* in livestock feed are needed to better understand and explore this underutilized drought resilient resource in various livestock feeding systems.

4.4. *Manihot Esculenta* Crantz

Cassava (*Manihot esculenta*) (Figure 4E), known for its drought tolerance, can be cultivated with minimal inputs in arid regions, making it a valuable crop for food and nutrition security. Its leaves and roots are the main components used for livestock feed, further supported by its ability to regenerate after defoliation caused by prolonged drought conditions. Moreover, the main cause of cassava cultivation is that it can be achieved without the inclusion of fertilizers, as outlined by OECD et al. [72]. Cassava can be effectively integrated into livestock feed systems, with various processing and nutritional enhancement techniques such as fermentation. It has been reported that solid state fermentation of cassava and its residues with *Pleurotus ostreatus* (Jacq.) P. Kumm (oyster mushroom) mycelium significantly increased protein content of the crop from 4.29 mg/100 g to 7.91 mg/100 g after the fermentation process [73]. A cassava foliage that included banana flour and grass hay resulted in increased presence of bioactive compounds in comparison with a foliage that lacked the inclusion of cassava. Amongst the chemical constituents analyzed, chromatographic analysis revealed the presence of isoginkgetin; a major occurring compound known to possess anti-inflammatory potency [74]. Certain novel bacteria, such as *Citrobacter freundii* 5519, isolated from cassava waste have been noted to possess the ability to reduce the occurrence of a toxic cyanide compound, consequently promoting livestock feed safety [75].

The potential of cassava leaves, roots, and byproducts as livestock feed has been studied (Table 1). Ogbuewu et al. [76] found that substituting maize with cassava on the diet fed to chickens significantly impacted FCR and average daily gain, with a growth performance of approximately 10%. Evidence from previous studies also showed positive effects of cassava on in vitro gas production, synthesis of volatile fatty acids, antipathogenic effect, carcass characteristics and digestibility parameters (Table 1). Evaluation of hematological indices from five-week aged chickens revealed a significant increase in white blood cells (lymphocytes) as result of including biodegraded cassava root compared to a treatment that contained maize. A 48-hour biodegraded cassava root meal recorded lymphocyte content of 47% while the control produced 42% [77]. Replacing up to 50% of feed concentrates with cassava tops and roots in beef cattle diets is a viable option, as it maintains feed intake, nutrient digestibility, and rumen fermentation without negatively impacting average daily gain. [78]. Yellow feather chickens fed 15% cassava root meal showed similar growth performance (thigh and breast muscle mass) to control birds, indicating that the meal is an ideal partial feed replacement [79]. However, to prevent suboptimal growth performance and carcass parameters, the inclusion levels of cassava in feed diets must be optimized.

4.5. *Opuntia Ficus-Indica* (L.) Mill.

Cacti (*Opuntia ficus-indica*) species are emerging as a valuable, drought-tolerant livestock feed alternative, offering solutions for livestock health, environmental sustainability, and economic viability, particularly in arid and semi-arid regions. Their high-water content, ability to thrive in dry environments, and potential to reduce reliance on traditional, often water-intensive, feed sources

make them a promising area of research and application in livestock feeding systems [80]. Among the family of cactus crops (*Cactaceae*), the prickly pear cactus is the most extensively studied species for its potential as a sustainable alternative feed source in livestock systems [46,81–83]. Extensive explorations of *Opuntia ficus-indica* (Figure 4F) for various applications, employing diverse plant parts, varieties, and methodologies have been done [82]. As a plant exhibiting remarkable survival and adaptability, different varieties of *Opuntia ficus-indica* have demonstrated the ability to sprout, develop cladodes, and achieve acceptable weight in watershed areas [84]. A proximate analysis of various *Opuntia ficus-indica* varieties revealed CP content ranging from 5.38% to 6.02% [85]. In their assessment of nutritional feed diets, Gebremariam et al [86] observed a notable presence of CP and soluble carbohydrates in *Opuntia ficus-indica*, with values of 83 g/kg DM and 251 g/kg DM, respectively. These figures exceed those of conventional basal diets, which contain 76 g/kg DM and 130 g/kg DM. This disparity proves the value of *Opuntia ficus-indica* as an alternative feed source, given its adequate CP and soluble carbohydrate content, which may be ideal nutrients for gut microbiota, and the energy needs of livestock.

The effect of *Opuntia ficus-indica* as feed on various livestock has been demonstrated producing positive results (Table 1). In goats, incorporating cactus pear silage at a 42% inclusion rate improved ruminating efficiency and water retention while reducing overall water intake without negatively impacting livestock performance [87]. A reduction in water intake is an ideal output when using cactus pear, especially during drought when water supply in farming systems is significantly limited. In the same study, evaluations of livestock productivity indicated that the inclusion of cacti in diets can lead to acceptable weight gains and satisfactory feed intake. Furthermore, the partial substitution of corn grain with *Opuntia ficus-indica* peel powder at inclusion levels of 5%, 10%, and 15% in Cobb chicken diets resulted in improved body weight, feed intake, and FCR compared to the treatment without inclusion of the prickly peel powder [88]. The incorporation of *Opuntia ficus-indica* in livestock feed diets is supported by various studies [12,82,83,89,90]. A recent investigation by da Silva et al. [12] proved that cactus-based diets are able to significantly reduce methane and ammonia nitrogen production (Table 1) better than alfalfa diets. These results suggest that cactus-based diets are sustainable and environmentally friendly as methane and ammonia nitrogen are considered hazardous to the environment.

Chequer et al. [91] found that adding *Opuntia ficus-indica* mucilage, at varying concentrations, to a lactose egg yolk extender significantly improved boar sperm quality after freezing and thawing. The study observed enhanced sperm motility, viability, and membrane integrity, suggesting that the mucilage is a beneficial addition to livestock reproduction. Moreso, adding cactus cladode powder to calf feed at a feed rate of 5 g/day significantly reduced the pathogenic bacteria *Escherichia coli* and *Enterobacteriaceae*, which are known to cause diarrhea in livestock. The antimicrobial effects were attributed to the high flavonoid content in the cactus cladodes [92]. While *Opuntia ficus-indica* is abundantly available in arid and semi-arid regions of Africa and could offer a solution to feed challenges, its use as a livestock feed, remains relatively under-researched. Thus, more research is needed to fully understand its role in livestock production, especially exploring the different components of the plants such as the fruit peel and various components from the cladodes such as fiber and mucilage. This strategy will assist in optimizing exploitation and realize the full potential of *Opuntia ficus-indica* in livestock feeding.

Table 1. Major selected drought tolerant crops and their application in livestock feed.

Crop	Processing method	Experimental model	Parameters measured	Key findings	References
Sorghum	Dried SDDGS	Thirty-two Hereford steers (331.2 ± 33.5 kg) were fed with SDDGS (0, 150, 300, or 450 g/kg) for 12 weeks. Control contained sorghum grain, sunflower meal and urea.	Performance indices such as intake and digestibility as well as carcass traits (hip weight, body weight and carcass weight) were evaluated.	An increase in the inclusion of SDDGS resulted in an increased intake of CP and GE. No significant changes were observed regarding carcass traits which suggest SDDGS as a viable replacement treatment.	[7]
	BMR mutant lines of sorghum samples were prepared into forage and dried at 65°C.	<i>In vitro</i> digestion using rumen fluid obtained from two fistulated Friesian Holstein cattle weighing approx. 525 kg.	<i>In vitro</i> digestibility dry matter and <i>in vitro</i> true digestibility were analyzed from the obtained samples.	Cultivar GH2.3 presented the highest digestibility of dry matter. Bioguma and GH2.3 had portrayed the highest relative feed value as it is determined through dry matter intake and digestibility. <i>In vitro</i> true digestibility of Bioguma was observed to be higher than the other tested cultivars.	[8]
	Whole green SW was harvested, chopped and sun-dried.	A total of 144 male Yuzhou goslings (28 days old) were fed with 0, 4, 8 and 12% SW.	Body weight, daily feed intake, average daily gain, blood composition, antioxidant capacity and intestinal morphology were evaluated.	SW levels increased, the geese's average daily gain decreased during days 28–49, while their average daily feed intake and feed/gain ratio increased during days 28–70. The plasma biochemical parameters, antioxidant capacity, and duodenal digestive enzyme activity did not differ among the groups	[9]
	The mixed fodder, with corn as the main component, was prepared by grinding, mixing and pelletizing	ROSS-308 chickens were fed mixed fodder containing 20–40% sorghum grain for 28 days.	Carcass characteristics, such as daily weight gain, were monitored during the experiments. Additional effects on chicken productivity were also observed.	During the second week of chicken rearing, average daily weight gain increased from the diet that consisted of 30% sorghum grain.	[10]
	Supplied sorghum seeds were stored in a dry environment and ground using a roller mill.	Twenty lactating buffalo cows were fed diets supplemented with sorghum or corn once a day for about 7 weeks.	Milk production, digestibility and carcass scores were analysed.	Chemical composition analysis revealed higher crude protein to be found in sorghum meals rather than in maize.	[11]

	Sorghum silage feed diet was developed using an ensiling technique.	Silage of varying proportions from corn and sorghum were fed to Holstein dairy cows that were at their mid-lactation phase.	Analysis of resultant serum metabolites was conducted on the samples at day 45.	Milk yield was better maintained by the diet that consisted of sorghum compared to the one that had maize. Chromatographic analysis of present chemicals in blood serum induced linoleic acid, succinic acid, 2-ethylacrylic acid, and glutamic acid levels.	[12]
Millet	Pearl millet samples were ground into powder.	A total of 300 laying hens were fed on a diet that contained various levels of pearl millet replacing 25, 50 and 75% of corn.	Every 4 th week hen weight and total feed consumption was recorded. Egg production was also noted on a daily basis. In addition, broiler performance was also determined on starter, grower and finisher broiler.	Broilers that consumed 0-14% whole pearl millet diet had higher body weight gain than those that consumed 28 and 43%.	[13]
	Gayamba pearl millet were purchased from local markets, boiled for 30 minutes sun dried for 4 days. The finger millet sample passed through roasting at 115°C for 15 min in an oven and ground into powder. The straw used was obtained as the result of finger millet processing by product.	A total of Cobb 500 broiler chicks were fed treatments containing starter and finisher diets replacing red sorghum. The feed formulations were prepared for chickens housed in well-ventilated cages.	Growth indices: daily feed intake, daily weight gain and feed conversion ratio were measured. Fat deposition assessments.	The total feed intake for Gayamba pearl millet diet was observed to be the highest at level 4 during the finisher period. Fat deposition was reduced while an increase in lean tissue was observed.	[14] [15]
	The pearl millet was obtained as a whole grain from a local supplier.	The formulated diets contained various amounts of finger millet straw which were fed to crossbred rams.	Carcass traits, the presence of blood metabolites and the resultant meat quality were assessed.	Average daily gain was higher in livestock that were fed 25% of finger millet straw. Blood metabolite analysis revealed high presence of total protein as far as the group fed 50% of finger millet straw. Increased weight of the gizzard and thick muscles such as <i>Musculus crassus cranioventralis</i> and <i>Musculus crassus caudodorsalis</i>	[16] [17]
	Black and red finger millets grains were purchased from a nearby market and milled into fine powder.	Feed formulations of 0, 25, 50, 75 and 100% made from black and red finger millets to replace maize were fed to	Carcass traits and relevant growth performance indices were assessed.	The chicks that were reared red finger millet had higher final weight compared to those that consumed black finger millet.	[18]

- broiler chicks who were 600 days old.
- Millet and corn sample preparation included drying at 65 °C and milling into fine powder before diet formulation commenced.
- Finger millet straw samples were formulated using the extrusion technique.
- Pearl millet grains were sterilized in a saline solution and left to sprout at room temperature for 3 days. Thereafter the sprouts were sun-dried.
- Pearl millet was obtained through the extrusion process and developed into varying degrees.
- Two methods (grinding and pelleting) were used to create a pelleted and mashed pearl millet-based diet.
- Feed rations were made out of CORM in an attempt to replace maize at various levels of 0-45% by weight created through milling to a size of 5 mm.
- Diets of different millet and corn combinations formulated before being given to cannulated cows.
- A total of 24 Mandya lambs were fed complete feeds that contained extruded finger millet straw.
- A sprouted whole grain millet was incorporated at 25, 50, 75 and 100% in starter and finisher diets of broiler chickens.
- The extruded pearl millet replaced maize at varying levels of 25, 50, 75 and 100% and fed to broilers.
- Varying levels of mashed and pelleted pearl were included in the diet at composition levels of 50, 75 and 100%, replacing maize in broiler chickens.
- A total of 192 Cobb chicks were used as experimental livestock, feeding them for 42 days.
- In situ* digestibility, assessment of ruminal composition and microbial diversity were investigated.
- Daily intake, dry matter intake and feed conversion ratio were assessed.
- Growth performance and organ development were analyzed.
- Carcass performance parameters were recorded.
- The consequent influence of the diet on the growth performance parameters portrayed by the broilers were analyzed.
- Dry matter intake, average daily gain and egg production were evaluated.
- Fungal population of *Basidiomycota* when cattle were fed a 50:50 mill: corn combination exponentially increased at 12th hour interval of sample analysis.
- Rumen *in vitro* gas production was observed in finger millet straw compared to extruded feeds from areca sheath and maize cob.
- Cholesterol levels increased with an increase in sprouted whole grain millet inclusion. Liver weight showed linear response to the incremental inclusion of sprouted whole grain millet.
- The treatment with 75% pearl millet achieved better live and breast weight gain.
- Pelleted diet did not influence the carcass characteristics of the broilers.
- The 45% *enset* corm feed resulted in a significantly higher dry matter intake compared to other treatments.
- [19]
- [20]
- [21]
- [22]
- [23]
- [24]

False banana	<i>Ensete</i> sample was chopped and dried using shade drying.	The feed constituted of <i>ensete</i> CORM, sude and wheat bran with a specific focus on the inclusion of <i>ensete</i> CORM as a partial replacement for wheat bran when feeding 42 intact male yearling rams.	Livestock feed intake, changes in body weight and feed conversion efficiency parameters were analyzed.	Body weight gain, during the 4 th feeding week was significantly enhanced amongst the dietary treatments that included 45g, 90g and 135g of <i>ensete</i> corn.	[25]
Cassava	Cassava residues were obtained as by products from cassava processing operations.	Cassava residues were included at different levels and fed to Holstein cows.	<i>In vitro</i> gas production analysis, analysis of microbial crude protein and ammonia were conducted.	An increase in cassava inclusion resulted in an increase in the pH after 48 <i>in vitro</i> incubations. Cassava was noted to decrease production of ammonia-N. Treatments that contained 15, 20 and 25% of cassava residues have shown notable production of volatile fatty acids.	[26]
	A blend of cassava peel and leaf was created at a ratio of 5:1. Fermentation using water and microbiome was used as an additional tool to various diets.	The created blend was then reared into 24 pigs for 16 weeks feeding trial.	Growth performance, haematological and biochemical parameters were measured.	The blend made from cassava parts did not negatively affect the measured parameters, suggesting a feasible replacement of maize.	[27]
	Cassava top and root were harvested from smallholder farmers, processed into small chips and the needed cassava top and root ratios were blended. The 40:60 ratio was processed into silos and ensiled for a period of 14 days.	The silage was fed to beef cattle at different inclusion rates replacing feed concentrates.	The pH, chemical composition, fermentation, carcass and blood metabolites were measured.	Digestibility of acid and neutral detergent fiber were observed to be higher at the silage that contained 100% of cassava top and root chips.	[28]
	Cassava peel was obtained as a byproduct from the cassava tuber processing.	A 7-week feeding trial consisted of rearing four diets to grower pigs.	Growth indices were analyzed.	Diet that contained 50% of cassava peel exhibited gains in total and average weight, total and average daily feed intake.	[29]
	A cassava root meal was obtained.	The cassava root meal was assigned to 140-day old chicks using for dietary compositions where percentages of cassava root were 15, 30 and 45%.	Nutrient digestibility, growth performance and organ development were assessed.	The study concludes a diet containing 15% of cassava root meal ideal to attain desired growth indices as well as chicken production.	[30]

	<p>Cassava pulp ensiled with or without the inclusion of <i>Lactobacillus casei</i> TH14 (LTH14).</p> <p>The sun-drying method was used to process graded cassava peels and used as an energy source replacing maize at treatment levels of 18.5-74%.</p> <p>A silage was prepared by chopping cassava leaves into pieces and then sun dried for 4 hours before being stacked under anaerobic conditions using plastics for 21 days.</p> <p>Cassava leaves and peels were fermented with <i>Citrobacter freundii</i> 5519.</p>	<p>The treatments were then assigned to Thai-native beef bulls².</p> <p>Sun-dried cassava peel diets were reared to pregnant goats on a weekly basis.</p> <p>Experimental diets were derived by including sun dried cassava leaves at levels of 10-30% before being fed to pigs.</p> <p>The fermented cassava peels and leaves were reared to Kamang ducks.</p>	<p>Growth performance and digestibility indices were screened.</p> <p>Growth performance parameters were analyzed.</p> <p>An analysis of growth and reproductive performance on pregnant pigs.</p> <p>Changes in carcass traits, growth performance and meat quality were recorded.</p>	<p>The cassava pulp ensiled with <i>Lactobacillus casei</i> TH14 (LTH14) produced higher crude protein digestibility and greater presence of volatile fatty acids.</p> <p>Treatment containing 37% sun dried cassava peel had higher average weight daily gain. In addition, 74% of cassava dried peel was commendable for Soloko goats.</p> <p>Feed conversion ratio increased with an increase in cassava leaves.</p> <p>Significant increases were observed in parameters such as weight gain and feed intake.</p>	[31] [32] [33] [34]
<i>Opuntia ficus-indica</i>	<p>Spineless cacti were procured from a nearby farm.</p> <p>The cladodes were harvested, chopped and used on a fresh basis alongside a forage made from a 5-year-old saltbush.</p> <p>A peel from a ripened fruit of cactus pear was sun dried and processed into powder to allow inclusion at various levels in order to be fed to chicken broilers.</p>	<p>Varying inclusions of spineless cactus at 20 and 40% were fed to 18 Nellore lambs that had initial weights of 20.5 kg.</p> <p>Awassi sheep were fed two ratios of spineless cladodes and saltbush.</p> <p>Commercial Cobb chickens were reared diets that were made up of prickley pear peels and yellow corn grain.</p>	<p>A 5-day nutrient digestibility trial was investigated in addition to proximate analysis of the diets.</p> <p>Nutritional parameters, digestibility, growth performance and the presence of blood metabolites were screened.</p> <p>Composition, carcass traits and histopathological results by the diets were investigated.</p>	<p>Nutrient digestibility of organic matter and dry matter was observed to be higher in treatments that contained cactus (20 and 40%) pear in their formulations. Water intake was observed to be low in Nellore lambs which is suggestive of cactus as a valuable option in areas where water scarcity is largely pronounced.</p> <p>Increasing the levels of cactus and saltbush in diets resulted in an increase in the digestibility of crude protein.</p> <p>Performance parameters such as feed intake, carcass traits such as live body weight as well as feed conversion ratio; were better with the consumption of diets that comprised of 5, 10 and 15% peel powder from cactus.</p>	[35] [36] [37]

- Opuntia ficus-indica* cladodes were sun dried for a period of 7 days and thereafter they were dried at 50°C for 2 days before being crushed into fine powder. The finely ground powders were fed into 3 groups of chicks with diets that contained 5 and 10% of *Opuntia ficus-indica* powders. The effects of *Opuntia ficus-indica* cladode powder were analyzed on the growth and carcass characteristics of the reared chicks. The 5% inclusion of *Opuntia ficus-indica* produced better body weight gain over the feeding trial of 42 days, compared to a control and 10% powder inclusion. With carcass characteristics 10% *Opuntia* powder inclusion produced better gain with weights recorded for liver, gizzard and abdominal fact [38]
- Opuntia ficus-indica* cladodes were tested on a fresh basis by including them in a pig diet. *Opuntia ficus-indica* was reared in gilts that were in their lactation and gestation phases. The influence of *Opuntia ficus-indica* on biochemical parameters such as concentration of glucose and insulin were assessed. Moreover, feed intake influence was also studied. The inclusion of *Opuntia ficus-indica* positively influences the levels of insulin in the blood of the gilts. Also, there was lower body weight loss. [39]
- Cactus cladodes were obtained from a farm and dried with direct sunlight for a period of 5 days. The dried cladodes were ground into fine powder using a hammer mill. Diets were formed with varying inclusion levels of cactus powder and reared to dewormed Nguni heifers. Livestock growth performance, carcass traits and cost benefit analysis were investigated. The diets containing 10 and 20% cactus cladode powder exhibited better feed conversion ratio than those with control or commercial feed. It was declared that the inclusion of cactus powder resulted in reduced expenditure on ingredients translating into a cost-effective strategy during the drought season when the prices of other commercial ingredients increase. [40]
- Cactus cladodes were harvested during the winter season and sliced before being in an oven at 55°C for a period of two weeks. The dried samples were fed into a rumen fluid that was collected from fistulated steers. Fermentation patterns, water intake and chemical screenings were conducted. During the fermentation process, cactus produced lower concentrations of ammonia nitrogen than alfalfa diets. Cactus had 6.64 mg/100 mL while alfalfa produced significant amounts of 25.1 mg/100 mL. With methane, cacti significantly produced lower levels of 2.2% compared to alfalfa that had 3.52%. [41]
- The mucilage was obtained from the cladode of *Opuntia ficus-indica* through squeezing of the pulp to get a liquid which was then The mucilage was applied in sperm freezing extenders at various concentrations using sperm that were obtained from boar cattle. The quality of the sperm obtained from boers was analyzed looking at motility, integrity, viability, morphology and motility. The addition of mucilage resulted in improved characteristics of the frozen semen without causing unwanted disorders. The viability and membrane integrity of the sperm was significantly [42]

centrifuged in order to keep the supernatant for analysis. The cladodes used in this study were sun-dried and oven dried for 14 and 4-5 days, respectively.

Powdered samples were then assigned to calves at 2.5g/day.

Livestock performance and faecal microbial count were analyzed.

improved by the 6.7% mucilage addition to the freezing extender.

A 10 post-partum investigation revealed [43] decreased faecal pathogenic population of *E. coli* and *Enterobacteriaceae*, as well as their total coliform count, when cladode powder was used.

Abbreviations: SDDGS= Sorghum dry distillers' grains with solubles; CP = Crude Protein; GE=Gross energy; BMR= Brown Midrib, SW= Sweet Sorghum.

5. Factors Affecting the Quality and Functionality of Drought-Tolerant Crops

This section discusses pre-harvest and post-harvest factors that affect the quality and functionality of drought tolerant crops. It further highlights how pre-harvest factors such as cultivar and maturity stage, and postharvest factors like processing and storage techniques impact the quality and functionality of the drought tolerant crops as livestock feed. In addition, the section explores how these factors collectively inform the economic feasibility for small to medium-sized livestock production businesses, especially in developing nations, where the impact of drought is more severe. These factors provide the foundation for optimizing the quality of drought resistant crops-based livestock feed.

5.1. Preharvest Factors

5.1.1. Cultivar

While the effect of cultivar type on crop production is well-studied in horticulture, there is a noticeable research gap regarding its influence on livestock feed crops, particularly drought tolerant crops. Despite this, there is growing interest in developing drought-tolerant cultivars for sustainable livestock production, as cultivar choice can impact nutrition, livestock performance, and overall drought resilience. Miron et al. [111] compared three newly developed sorghum hybrids (Supersile 20, Silobuster, and Brown-Midrib Hybrid BMR-101) against a commercial variety (FS-5) and observed that the latter performed better than the experimental hybrids. In another study, a total of eight sorghum cultivars (Jawar-263, = F-1017, Jawar 2002, F-114, Hegari, Sandal Bar, Sorghum, MR-2011, Pak-China-1) were assessed for their fodder yield characteristics, revealing that parameters such as stem diameter, leaf weight per plant, DM yield, and forage yield were higher in the Puk-China and F-114 cultivars. Additionally, higher levels of crude fiber and CP were observed in the cultivars F-7017 and Sandal Bar [112]. Reports from Bean et al. [113], Pinho et al. [114], Neto et al. [115] and Sajimin et al. [116] have demonstrated the influence of cultivar on the nutrient composition, yield, digestibility, agronomic traits, and fermentation profiles of sorghum-derived forages. BMR cultivars exhibited the highest NDF digestibility, while cultivar BRS Ponta Negra showed high contents of WSC, produced greater contents of lactic acid compared to other cultivars [114]. Other studies showing the interaction between sorghum varieties, nutritional, chemical and digestibility parameters have been reported by Wahyono et al. [94] and Kapustin et al. [117].

Several cactus species can be used as livestock feed, including *Opuntia lindheimeri* Engelm., *Opuntia ficus-indica* (L.) Mill., *Opuntia stricta* Haw., *Opuntia engelmannii* Salm Dyck., *Opuntia ellisiana*, *Opuntia rastrera* Weber, *Opuntia chrysacantha* Berg, *Opuntia amyclae*, and *Nopalea cochenillifera* Salm Dyck. According to Dubeux et al. [81] *Nopalea cochenillifera* Salm Dyck. exhibited superior WSC, DM, and IVOMD. The replacement of Miúda (*Nopalea cochenillifera* Salm Dyck) with a newly engineered genotype known to be Orelha de Elefante Mexicana (*Opuntia stricta* Haw.) managed to linearly increase microbial protein even though other traits such as DM digestibility, CP, total digestible nutrients and OM decreased with an increase in the replacement proportion of the diets [118]. Conversely, the replacement with Orelha de Elefante Mexicana (*Opuntia stricta* Haw) contributed to the maintenance of milk production in Girolando cows with a recorded measure of 12.5 kg per day. Assessment of nutritional variation amongst *Opuntia* varieties species established that higher levels of pectin was relatively found in erect prickly pear (*Opuntia stricta* Haw) than in Gigante (*Opuntia ficus-indica*), IPA-20 (*Opuntia ficus-indica*), F-08 (*Opuntia atropes* Rose) and African Prickly Pear (*Opuntia undulata*) [119].

In a comparative assessment of genotypes within the *Opuntia ficus-indica* species and those of *Nopalea cochenillifera*, Ramos et al. [120] noted that the cultivars Tamazunchale, Negro Michoacan, and California from *Nopalea cochenillifera*, as well as Orelha de Elefante Mexicana and Amarillo, performed better with respect to dry yield, green mass and WUE. The superior performance of these cultivars can be attributed to the distinct genotypic traits, which include the number of cladodes per

plant, cladode dimensions (length, width, diameter, and thickness), as well as overall plant height and width [120]. In this sense, it can be postulated that a greater expression of specific genotypic characteristics correlates with improved performance outcomes. After assessing the performance of cladodes from sixteen cultivars of *Opuntia* based on digestibility and proximate parameters, it was observed that the cultivars Aloqa, Garao, and *Opuntia robusta* var. X11 exhibited the highest levels of similarity (65-98%) when multivariate analysis was conducted [121]. In a proximate analysis of *Opuntia* species, Keyih (*Opuntia ficus-indica* spp.) had the highest DM content recorded to be 91.88%. Ash content was highest in *Opuntia ficus* spp. cultivars Lemats and Sihuna, while *Opuntia stricta* var. Mexicana had the lowest ash content. *Opuntia ficus* and *robusta* species showed the lowest OM content. *Opuntia stricta* var. wild had the highest NDF (67.05%), and *Opuntia stricta* var. Mexicana had the lowest (37.21%). The reported fiber values were above the recommended ones in South African livestock feed (28%), demonstrating the potential of these studied species and cultivars in enhancing livestock nutrition [122].

Alves et al. [123] analyzed seven *Opuntia* cactus cultivars, focusing on cladode characteristics to understand morphological and nutritional variations. The study observed significant differences in traits like cladode number, length, width, area, and thickness across the cultivars, highlighting their diverse nature. In a rainfed region, the Orelha de Elefante, F-08, and Gigante cactus cultivars demonstrated superior photosynthetic performance compared to other tested varieties (Orelha de Elefante Mexicana, V-19, Redonda, F-08, and Orelha de Elefante Africana, Clone IPA-20) after propagation and harvesting [123]. The larger the total photosynthetic area of the cladodes, the more efficient they are in energy production and bioavailability for the feed livestock. Mineral content, in moderate amounts, of a feed source is essential to the overall nutritional value of a feed diet. For instance, phosphorus is known to be crucial for skeletal development, cellular signaling and nucleotide build up, when found in adequate concentrations [124]. Alves et al. [123] found that phosphorus distribution in certain cactus pear cultivars (Giganta, Redonda, V-19, and F-08) is significantly influenced by their genetic differences, with these cultivars showing the highest phosphorus concentration at cladode order 4.

The studies discussed above have demonstrated that morphological traits are positively linked to both dry and fresh mass production, suggesting a strong connection between cultivar and livestock feed outcomes. Thus, breeding programs focusing on these variations could help address feed shortages through optimizing the desirable traits. In addition, cultivar and harvest maturity are closely related because the maturity of a crop at harvest is heavily influenced by its specific cultivar. Meanwhile, different cultivars of the same crop can mature at different rates and reach their peak quality at different times, suggesting that they should be harvested at different stages of maturity.

5.1.2. Harvest Maturity

The maturity of a crop is intrinsically linked to its biological processes, nutrient composition, physical development, and overall plant growth [125]. Consequently, harvest maturity is typically employed as an indicator to ascertain the optimal timing for harvesting of some crops intended for human consumption [126]. Numerous studies have explored the relationship between nutritional composition and harvest maturity in general crops, yet there has been comparatively less focus on drought-tolerant crops, particularly those intended for livestock feed.

Four drought-resistant sorghum cultivars (Early Sumac, Leotti, Nes, and Rox) exhibited varying performance when evaluated at distinct harvesting stages: panicle emergence, milky, dough, and physiological maturity [127]. The study identified the physiological maturity stage as the optimal time for harvest due to the high yield and superior fodder quality by sorghum cultivars [127]. This is probably because the physiological maturity stage represents a period of continued plant development post-harvest, which results in an increased yield and fodder quality. However, lower values of ADF (53.9%) and NDF (30%) were recorded during the milky to dough maturity stages, which justified the ensilage of sorghum BRS-610 to improve these attributes as these harvesting periods ensure acceptable fermentation and good nutritive value [128]. During the assessment of

different maturity stages of sorghum silage and fodder, the hard dough and physiological maturity stages exhibited better nutritive value and fodder yield [129]. More studies demonstrating the influence of harvest maturity stages on sorghum cultivars have been published by Terler et al. [130], Silva et al. [131], Alatürk [132] and Hakim [133]. Three varieties (categorized according to silage, biomass and grain) commonly utilized for producing whole crop sorghum silage for ruminants were evaluated for their differences in nutritional values (Table 2). It was found that, across all three tested maturity stages, DMY was significantly greater in the variety classified under the biomass group compared to the other varieties [130]. Harvesting during the 3-week stage or boot stage resulted in higher CP and total digestible nutrient content, and lower fiber, while the dough stage yields more DMY but lower nutritional value [130]. Nonetheless, the study recommended the dough stage as the optimal maturity stage for enhancing nutritional levels in grain sorghum varieties.

Four maturity stages, spaced over three weeks—boot stage, flowering stage, and dough stage—had varying effects on the quality and yield of Johnsongrass. In this study, Silva et al. [131] observed that the first harvest at three-week and boot stage maturities were characterized by elevated levels of CP concentrations and total digestible nutrients. The study recommended that Johnsongrass should be ensiled before reaching the flowering stage as this is the optimal phase that produces desired silage qualities [131]. An assessment of the quality of sweet sorghum and sorghum sudangrass hybrid cultivars harvested at early and late growth stages revealed that dry yield increased with plant maturity, recording a remarkable 172.2% increase in forage at the late growth stage [132]. Silva et al. [131] identified significant agronomic differences between sorghum green fodder and maize harvested on days 6 and 12, with the latter yielding the highest plant biomass, while the former produced the lowest. Furthermore, Moura et al. [134] expanded the investigation into sorghum maturity stages by assessing DM intake, digestibility parameters, and methane production in sheep. Organic and DM digestibility were observed to be induced with an increase in maturity stage that was measured at day 121 of harvest.

Despite some studies reporting that the chemical and physical properties of *Opuntia ficus-indica* are influenced by various maturity stages, they do not provide additional insights regarding its application in livestock feed. This presents an important research gap that needs to be addressed. These studies can serve as a foundational basis for further investigation into the effects of maturity on *Opuntia* spp in the context of feed utilization. Research conducted by Juhaimi et al. [135] demonstrated that prickly pear fruits harvested at 15-day intervals from June 15 to August 15 exhibited significant variations in their fatty acid composition and bioactive compounds. Notably, the highest concentrations of phenolic compounds, measuring 156.77 ± 0.09 mg GAE/100g, were recorded from the harvest on July 1, after which a decline to 121.61 ± 0.09 mg GAE/100g was observed [135]. In contrast, antioxidant activity, as measured by inhibition against 2,2-diphenyl-1-picrylhydrazyl (DPPH), increased with advancing maturity. This discrepancy may be attributed to the role of other bioactive compounds, in addition to phenolics, that might also contribute to antioxidant activity. Furthermore, the fatty acid composition revealed the emergence of compounds such as linolenic, behenic, and erucic acids from July 1 harvest through to August 15 [135].

Table 2. Effect of maturity stage on the nutritional and chemical characteristics of drought resistant crops for livestock feed production.

Crop type	Maturity stages	Key findings	Reference
Sorghum	Milky, milky/dough, dough, dough/dent, dent, hard, dry	Dry matter of the silage increased with grain maturity from 199 to 473g/kg. Increments in pH levels were observed as a function of grain maturity which ensures good quality conservation of the silage.	[44]
	Panicle emergence, milky, dough, physiological, bloom	As each plant matures characteristics such as dry matter, plant height, protein content, and relative feed value also increased. In addition, physiological maturity stage was advised at the suitable time for harvest as qualities of the fodder and high yield attributes were observed.	[45]
	Bloom, soft, hard, physiological,	Highest dry matter was obtained when the plant was harvested at physiological maturity. Highest <i>in vitro</i> dry matter digestibility was observed at bloom stage with a record of 60.72. Conversely, fodder made from hard dough maturity stage yielded higher nutritive value when looking at elements such as crude protein, neutral and acid detergent fiber as well as acid detergent lignin.	[46]
	Late milk, dough, full maturity	Dry matter yield was enhanced between late milk and dough stages. Silage made from the whole crop produced a significant increase in metabolizable energy (ME) during late milk and dough maturity stages.	[47]
	3 weeks, boot, flower, dough	The flower maturity stage harvest displayed high content of dry matter. Crude protein was declared low in the 3-week harvest while high in the dough stage.	[48]
	6 th , 12 th day	The 12 th day harvest produced the highest plant biomass compared to 6 th day harvest.	[49]
	Mid early, late	Crude ash content decreased with an increase in crop maturity.	[50]
<i>Opuntia ficus-indica</i>	Milk, soft mass, hard mass, mature	Digestibility of dry matter increased with an increase in crop maturity.	[51]
	Maturity measured at 15-day intervals.	Phenolic content was found to be 156.77 mg/100 g during the first harvest while the second harvest, known to be last stage maturation, produced elevated antioxidant capacities.	[52]
	Young, intermediate, mature	Young and intermediate phases of African and Erect Prickly Pears species exhibited elevated nutritional parameters that were regarded relevant for ruminant health.	[53]

Early small sized, young cladodes	Medium sized and aged cladodes exhibited appreciable antioxidant activity while early harvested cladodes had lower antiradical activity when tested using the ORAC test. Cell viability studies revealed minimal toxicity of the differently harvested cladodes with concentration ranging between 0.01 and 0.1mg/mL.
-----------------------------------	---

ORAC= Oxygen Radical Absorbance Capacity.

Cladodes from various *Opuntia* species, cultivated at different developmental stages for use in ruminant feeding, demonstrated that parameters such as DM, NDF, and ADF increased with maturity across all tested varieties, while CP exhibited an inverse relationship [119,136]. The elevated levels of NDF and ADF may indicate reduced digestibility of the feed, attributable to the composition of plant cell wall structures, specifically cellulose and lignin, which are typically resistant to breakdown by digestive enzymes and gut microbiota, especially in monogastric animals. A high DM content reflects the availability of other nutrients in the forage, which may enhance the overall nutritive value of the feed. Notably, young cladodes from *Opuntia ficus-indica* (IPA-20) and *Opuntia atropes* Rose (F-08) exhibited high mineral matter concentrations, with respective values of 95.5 g/kg DM and 133.5 g/kg DM. The erect prickly pear (*Opuntia stricta* Haw) also demonstrated substantial mineral matter content, recorded at 120.0 g/kg DM during the intermediate maturity stage [119]. Furthermore, the study conducted by [136] confirmed that the *Opuntia stricta* Haw cultivar contained significant phosphorus levels at the mature stage. Mineral matter analyses by Pessoa et al. [119] and specific phosphorus content assessments by Silva et al. [136] revealed that mineral content increased with maturity in African prickly pear cladodes. Maiuolo et al. [137] investigated the influence of three phenological stages of *Opuntia ficus-indica* cladodes on their antioxidant and anti-apoptotic properties. The findings indicated that early or young cladodes exhibited the lowest antioxidant activity compared to other developmental stages, while medium-aged cladodes demonstrated the highest antioxidant levels and these results were corroborated by the low DPPH inhibition values observed at the same developmental stage. Additionally, the maturity of *Opuntia ficus-indica* showed potential in mitigating apoptosis via the pretreatment of cells with extracts from late-aged cladodes, prior to exposure to lipopolysaccharides for 24 hours, which resulted in increased cell survival [137]. These results suggest potential implications for *Opuntia ficus-indica* for enhancing livestock health at a cellular level.

5.2. Processing Factors

The quality of livestock feed from drought tolerant crops cannot be fully optimized without the consideration of postharvest management and processing techniques [138]. Properly managed postharvest practices, activities and carefully implemented processing techniques are crucial, as they serve as primary determinants of whether the desired qualities of products derived from fresh produce can be retained, enhanced or degraded [139]. As such, this section focuses on how postharvest factors such as storage, and processing factors such as pulverization, drying and ensiling impact the quality and functionality of the developed livestock feed products.

5.2.1. Drying Techniques

Numerous studies have demonstrated that drying techniques can impact on the quality attributes of various food and feed products. In the context of livestock feed production, however, the application of drying methods to drought tolerant crops appears to be less prevalent, as evidenced by the scarcity of studies addressing research on drying technologies applied in drought tolerant forage with the objective of improving feed quality. Among the available drying methods, sun-drying is the commonly utilized technique in the processing of livestock feed. The prevalent application of sun drying in most farming operations can be due to limited accessibility to innovative drying techniques and machinery. In spite of this, sun drying technique has long proven the capacity of producing livestock feed worth of desired qualities in various farming systems due to its convenience and access. The supplementation of sun-dried *Atriplex halimus* L. foliage with exogenous enzymes exhibited a superior recovery of secondary metabolites in the gastrointestinal passage when compared to fresh foliage [140]. This investigation posits that sun-dried foliage provides a greater substrate availability for enzymatic action than its fresh counterpart. Furthermore, the increased levels of secondary metabolites in sun-dried feed indicate enhanced bioavailability and bio-accessibility of compounds, which may confer various health benefits, including antiparasitic properties, improved immunity, and methane reduction, among others [140].

Ramsumair et al. [141] investigated the effect of five different drying techniques (oven drying at 70 and 60°C, sun drying, shade drying and freeze drying) on drought-tolerant species including *Trichanthera gigantea* (Bonpl.) C. Mart, *Leucaena leucocephala* (Lam.) de Wit, *Morus alba* L, and *Gliricidia sepium* (Jacq.) Walp. Their study recommended shade drying over sun drying for the preservation of feed quality, while freeze drying or oven drying were recommended for laboratory analysis of feed based on the differences in quality attributes observed [141]. Different drying methods produce varying results that could also be influenced by the type of crop processed, on parameters such as ash content, NDF, ADF and acid detergent lignin (ADL). For instance, the freeze-drying option led *Morus alba* to record the lowest values of NDF, ADF and ADL, compared to other plant species dried by the other techniques previously mentioned. Freeze-drying technique could not reduce the NDF of *Trichanthera gigantea* as it was the highest amongst all other techniques with shade drying exhibiting the lowest value of this element. Sun drying was observed to lower the ADF on *Trichanthera gigantea* species better than other methods. Oven drying at 60°C produced the lowest ADF values when dehydrating *Gliricidia sepium* plants [141]. The study observed that the interaction between the drying technique and the type of plant species studied played a role in the quality of the final product. Even so, these drying techniques were able to reduce the content of fibrous elements in the samples studied, which is a key indicator of efficient digestibility of livestock forage.

Proving how a drying technique is a direct link to feed intake and digestibility, solar drying of *Gliricidia sepium*, *Leucaena leucocephala*, and *Cenchrus purpureus* (Schumach.) Morrone demonstrated greater palatability than fresh forage [142], while it exhibited lower DM content (17.86%) compared to sun-drying (21.47%) and oven drying (24.45%). These results allude to the fact that drying can enhance the composition of a forage or a feed. A study by Suwignyo et al. [143] found that oven-dried commercial alfalfa for poultry feeding had higher levels of amino acids compared to fresh alfalfa. Essential amino acids such as L-histidine, L-isoleucine and L-valine were relatively similar between the two treatments (oven-dried and fresh), suggesting that temperature (55°C) did not compromise protein concentration. These findings suggest that a carefully chosen drying process can improve the nutritional composition of forage or feed. However, sufficient evidence to support such findings is lacking as research on drying technologies such as freezing drying, hot air drying, oven drying or their combination in livestock feed is limited.

This scarcity can be attributed to the inaccessibility of modern drying equipment in rural farmsteads and the high procurement costs associated with such machinery. Nevertheless, these contemporary drying methods are recognized as the most efficient and convenient agro-processing technologies capable of meeting the demands of the feed industry. For instance, freeze-dried wild cactus cladodes have demonstrated excellent dietary fiber values when processed into flour [144], even though the flour was not intended to be used in livestock feed formulation. Furthermore, freeze-dried wild cactus cladodes exhibited higher concentrations of phenolic compounds and flavonoids compared to other drying techniques, such as tunnel, fluidized bed, and spray drying [144]. Recent research by Ferreira et al. [145] indicated that the food dehydration method could recover higher phenolic content of 0.5 mg GAE/ml in prickly pear, compared to 0.16 mg GAE/ml achieved through microwave drying. Oven-dried (50°C) cladodes from spineless *Opuntia ficus-indica* f. *inermis* and spiny *Opuntia amyclae* yielded comparable chemical compositions, volatile fatty acids, and gas production parameters during ruminal fermentation studies [146]. Although this investigation did not specifically emphasize the effects of drying concerning ruminant fermentation, it can be reasonably inferred that drying cactus cladodes at 50°C yields acceptable nutritional values. Notably, a consistent increase in gas production was observed during the ruminant fermentation experiments between winter and summer oven-dried cladodes, with the highest recorded value of 136.8 ml/0.5g from the summer samples after a 72-hour period.

Aruwa et al. [147] concluded that freeze-dried *Opuntia ficus-indica* pulp and peel exhibit superior antioxidant activities compared to oven-dried extracts. In the same study, the methanolic freeze-dried extract demonstrated an 18.8 mm zone of inhibition against gram-negative methicillin-resistant *Staphylococcus aureus* (MRSA), a microorganism recognized as detrimental to livestock health. The

observed inhibition of MRSA by the freeze-dried peel supports the notion that drying technology enhances essential biological activities of *Opuntia ficus-indica* within the feed industry. Gouws et al. [148] reported superior performance of microwave-dried prickly pears over freeze-dried samples in terms of total phenolic content, recording 149 µg GAE and total flavonoid content of 76.6 µg CE. A recent comparative study of silage versus solar-dried cactus forage revealed that the latter is more beneficial, as solar-dried cactus forage exhibited higher protein content than ensiled forage while preserving excellent nutritional quality [149]. Studies by Pastorrelli et al. [46] and Maniaci et al. [150] elucidates the significance of dried *Opuntia ficus-indica* in ruminant diets and its substantial contribution to daily milk quality, particularly focusing on cladodes. It is important to note that the drying of drought-tolerant crops remains underexplored, despite the common practice of forage drying on farms. The limited research on the application of drying techniques in feed formulation underscores the need for researchers to initiate investigations aimed at improving forage quality through various methods, including freeze drying, oven drying, and solar drying, either individually or in combination.

5.2.2. Grinding and Pulverization

Mechanical processing during the postharvest phase, both before and after storage, significantly impacts the techno-functional properties, chemical composition, and biological integrity of livestock feed. Grinding has been used as the most suitable mechanical technique in feed technology since it converts a coarse feed into a finer particle sized powder through physical separation of the fibrous matrix that holds the material intact [151]. The influence of grinding feed from drought resistant crops has been studied in relation to feed intake, gut health, nutrient digestibility, growth performance, feed palatability and quality by several authors [152–157]. Overall, grinding or pulverizing produced positive results towards livestock such as poultry and pigs. For instance, sorghum and barley ground to 0.3-0.9 mm and 0.43- 1.10 mm particle sizes, respectively, managed to reduce stomach ulcers in pigs [153]. Pulverizing increases surface area which enhances availability of nutrients for the digestive system and commensal microbiota found within the gastrointestinal passage [158].

Feed particle size reduction through grinding was reported to reduce proventricular weight of chickens, preventing the occurrence of a deadly proventricular dilation disease that severely impairs nutrient absorption efficiency in poultry [154]. Research is also exploring the use of varying grinding technologies, and their combination that can turn livestock feed ingredients into powder with better functional properties to livestock [157,159–161]. Grinding plant waste materials such as beet pulp and sunflower husks have resulted in acceptable increments of essential amino acids and reduction of fiber to appreciable values [160]. In addition, using different designs of crushers (open and closed), has shown that changing sieve parameters has a significant impact on the quality of the processed grain [159]. A normally ground diet with low fiber received high feed intake (76.5 g/ day) compared to a low fiber coarse ground that expressed feed intakes of 67.4 g/day. Also, growth rate and liveweight per day were better in this dietary treatment during the weaning days of the tested rabbits [161]. These studies solidify the effect of various grinding and pulverizing methods on livestock feed, performance, and products.

5.2.3. Ensiling

Silage production, also called ensiling, is a long-standing feed preservation method that is crucial for maintaining forage quality and ensuring livestock feed, especially in areas affected by droughts [162]. Due to the adverse edaphoclimatic conditions exacerbated by drought, ensiling of drought-tolerant crops or other forages remains a critical strategy, particularly in agricultural operations that lack adequate processing machinery and storage facilities [163]. The ensiling process is facilitated by natural anaerobic fermentation phenomena largely dominated by lactic acid bacteria (LAB) and yeasts microorganisms during the four main phases, which are initial aerobic, intense anaerobic fermentation, stable and feed (Figure 5). These microbes are able to convert OM into various products, predominantly lactic acid, assisted by the absence of oxygen and an acidic pH

environment [164]. In addition, ensiling converts unpalatable residues into health-beneficial chemical compounds for livestock, improving rumen degradability of cereal starch and allowing the amalgamation of different feed sources without compromising quality or introducing undesirable complexities [163].

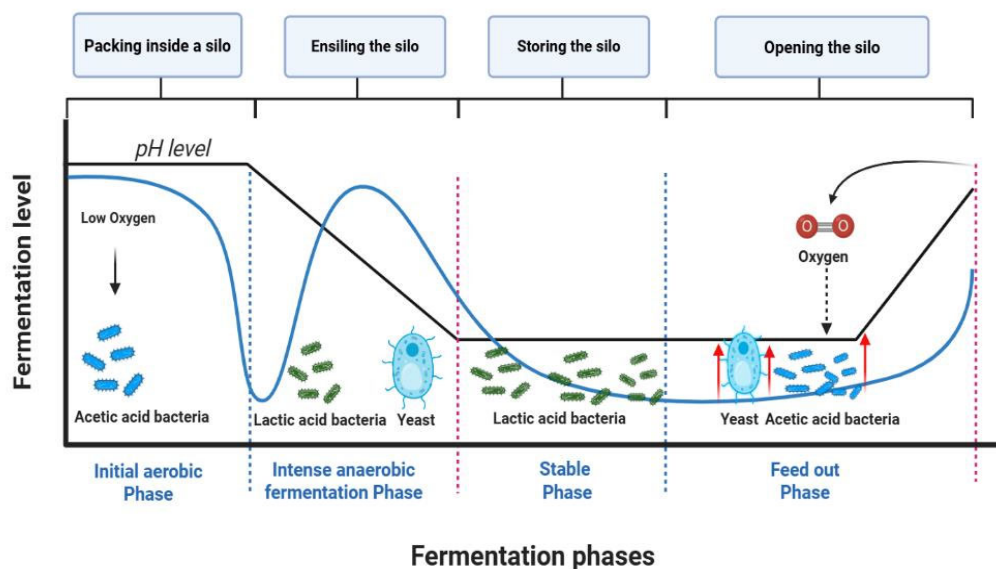


Figure 5. Anaerobic fermentation process occurring under four main phases during the silage production. Created in BioRender.

The impact of ensiling on drought tolerant crops has been studied. Lima et al. [41] demonstrated that ensiling two varieties of sorghum in combination with soybeans yielded superior silage results by improving quality characteristics such as pH, fermentation acids and ammonia nitrogen calculated from total nitrogen, compared to silage produced solely from soybeans. These findings demonstrated that favorable fermentation parameters were significantly enhanced due to the incorporation of sorghum. The mixed silage produced a more favorable pH outcome (4.03) compared to soybean silage alone (5.47). Lower pH due to higher concentrations of lactic acid is generally preferred for proper silage quality [41]. The amount of ammonia nitrogen derived from total nitrogen was significantly less in mixed silage (3.22 gNH₃-N/100gN) than the silage made from soybeans only (18.4 gNH₃-N/100gN). It must be noted that high ammonia levels indicate potential toxicity of the feed. In addition, the duration of ensiling process has been studied to contribute to a significant influence on the final characteristics of silage. For instance, ensiling sweet sorghum for 30 days resulted in marked increase in DM and CP in comparison to fresh samples [165]. Further increasing the ensiling process to 120 days increased ADF and ADL, which decreased in vitro digestibility of the feed. Prolonged ensiling also enhanced the fermentation process, producing increased levels of lactic and acetic acid contents. In a silage prepared from stylo (*Stylosanthes guianensis* (Aubl.) Sw.), a drought tolerant crop commonly used for livestock nutrition, low levels of ammonia-nitrogen and pH after 45 days of ensiling were noted [166]. Optimization of this ensiling technique concluded that the addition of an engineered LAB xg significantly increased in vitro DM digestibility of the forage with values of 68.57% compared to control that had 59.78% [166]. Insignificant degrees of acetic acid are considered an excellent measure of good silage quality. Ensiling varieties of alfalfa (*Medicago sativa* L.) have been proven to result in augmented chemical and fermentation qualities of the forage [167]. These studies demonstrate that ensiling duration and addition of supplements results in varying feed features that can be used to optimize nutritional characteristics of livestock feed.

It is worth highlighting that pathogenic bacteria may grow during ensiling process, and therefore developing additional precautionary measures is advised. In an attempt to address this,

Forwood et al. [168] demonstrated that ensiling drought-tolerant sorghum in conjunction with various types of common vegetables such as pumpkin or carrot can foster a beneficial microbial population conducive to livestock health, while suppressing pathogenic microbes. The microbial diversity observed as a result of increased vegetable inclusion was predominantly characterized by *Lactobacillus* species, with a lesser fungal population that included *Kazachstania humilis*, *Monascus purpureus*, *Issatchenkia orientalis*, and *Fusarium denticulatum* [168]. High levels of *Lactobacillus* lead to high lactic acid production which is an efficient compound that can inhibit spoilage-causing microorganisms in livestock feed. Even so, it is crucial to emphasize that the existing literature on the ensiling of drought-tolerant crops underscores the need for further research focused on optimization, integration of diverse feed sources, prevention of microbial spoilage, and the influences of harvest maturity and ensiling duration. These factors may significantly enhance current ensilage practices.

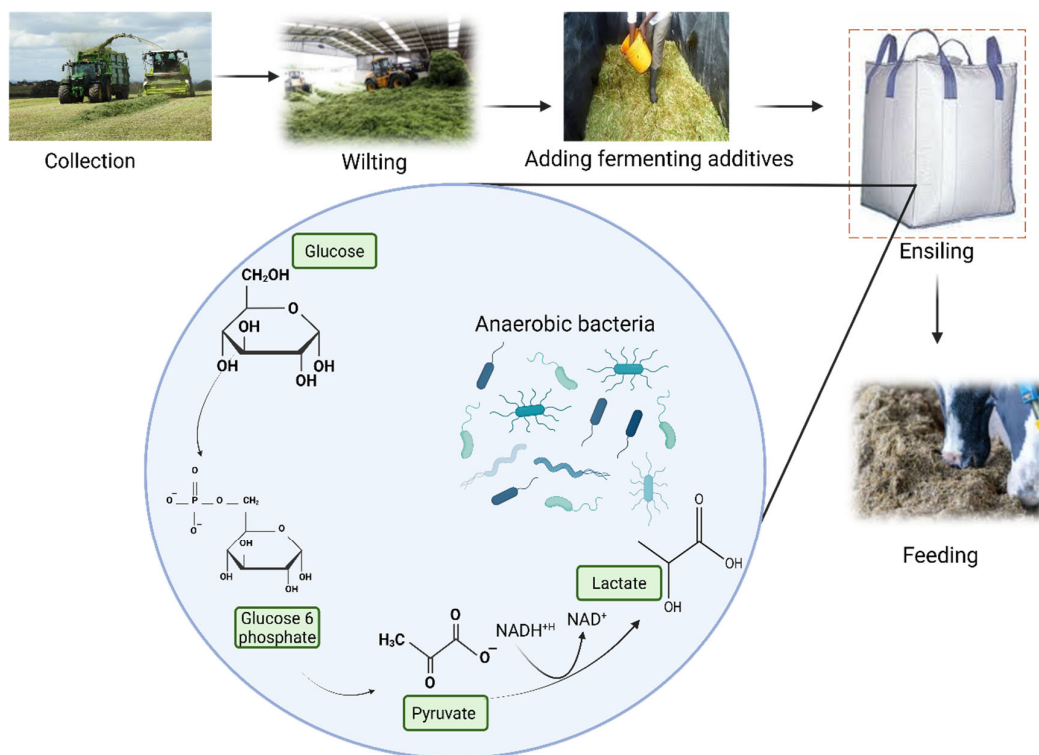


Figure 6. Common silage making process where a crop or silo is collected and wilted for a period of 24-36 hours before the addition of fermenting additives. Created using BioRender.

5.2.4. Storage

Precise storage conditions after harvest are crucial for maintaining the quality of agricultural commodities because plant metabolism continues even after the produce is separated from the soil. Proper postharvest handling, including storage, significantly impacts the physiological state and shelf life of the produce [169]. As such, the fundamental aim of any postharvest storage method must be to delay physiological processes that lead to quality deterioration through the limitation of metabolic pathways and pathogenic invasion that favor quality decline, while extending shelf life and maintaining ideal nutritional value [170]. Therefore, the effects of various storage conditions on the quality attributes of drought tolerant crops require investigations. Temperature is a key factor in post-harvest storage, significantly impacting the nutritional value and safety of a feed. High temperatures can accelerate spoilage, reduce nutrient content, and even lead to the growth of harmful microorganisms, affecting livestock health and productivity, while low temperature slows down respiration and metabolic processes [171].

Wang et al. [172] discovered that low temperatures of 5 °C are able to prevent microbial spoilage in wet brewers' grain by-products from barley that are usually used as livestock feed. Low temperatures have been reported to alleviate the growth and proliferation of *Aspergillus parasiticus*, known to cause the generation of aflatoxin in livestock feeds [173]. According to Manna et al. [174] temperatures around 8 °C are known to inhibit the growth of aflatoxins in grains during storage. During the storage of barley grain feed, high temperatures around 35°C exhibited the worst surface spoilage after 36 hours of storage. Further increase in temperature significantly decreased CP and WSC [172]. The study demonstrated that high storage temperatures can deplete amino acid content in livestock feed and further cause unwanted growth of fungi, bacteria and insects [175]. A temperature range of 26-37°C was observed to cause insect infestation, particularly *Rhyzopertha* spp, in sorghum ingredients that are usually used as raw materials for cattle feed [175]. In addition to insect infestation, aflatoxins may also grow in feed stored under high temperatures posing a threat to livestock health, performance and productivity [176]. Kirigia et al. [177] has drawn conclusive evidence-based perception on how ambient temperature is one of the factors that principally contributes to the decline of quality attributes specific cowpea. During the analysis it was observed that storing cowpea leaves at ambient temperature range of 20-25°C resulted in a decline of starch and sucrose while there were no noticeable changes observed under 5°C storage temperature. Alternatively, ambient and high temperatures have been reported as safe for the storage of dry livestock feed sources. Using a closed system, a temperature range of 15-25°C produced suitable nutritional parameters of lentil grains [178]. Based on the few studies found in literature, there is a noted research gap regarding the studies on effects of various storage conditions on the final quality of livestock feed made from drought tolerant crops.

6. Challenges of Using Drought Tolerant Crops as Livestock Feed

Drought-tolerant crops face significant challenges despite their resilience: they remain susceptible to disease infestation, are often characterized by low protein levels and high fibrous content and further suffer from low awareness which hinders their widespread adoption as climate-smart agricultural solution. The subsequent section of this review explores these limitations regarding the full integration of drought-resistant crops into daily farming operations.

6.1. Disease and Mycotoxins Infestation, and Feed Safety

Just like any type of agricultural crop, drought tolerant crops are vulnerable to disease-occurrences. For instance, *Opuntia ficus-indica* cladodes are unfortunately prone to diseases that are difficult to pinpoint to specific pathogens. The high-water content of these cladodes is believed to be a major contributor to disease susceptibility, as it creates a favorable environment for microbial growth [179]. Fungi such as *Alternaria tenuissima*, *Lasiodiplodia theobromae*, and *Fusarium* have been isolated from South African *Opuntia ficus-indica* cladodes, extensively studied and discovered to exhibit symptoms such as chlorosis, necrosis, and black gum exudation [179]. Molecular analyses of fungi isolated from *Opuntia ficus-indica* cladode lesions have confirmed the presence of *Alternaria alternata*, *Colletotrichum gloeosporioides*, *Fusarium lunatum*, and *Curvularia lunata* [180]. Recently, black spot disease has been identified in cactus cladodes cultivated in the Mexican region. Among six fungi responsible for inducing black spot symptoms, three have been classified as significant pathogens: *Alternaria alternata*, *Neoscytalidium dimidiatum*, and *Corynespora cassiicola* [181]. Black spot diseases are typically exacerbated by environmental factors such as high temperature and humidity, conditions that are intrinsic characteristics of drought. These findings underscore the vulnerability of *Opuntia ficus-indica* to various fungal pathogens, which limits the plant's yield potential and increases disease transmission to the livestock and possibly humans. During drought conditions, certain diseases may be favored while others are suppressed; however, pathogenic infections remain a significant threat to the diversity of drought-tolerant plants. For instance, charcoal rot disease, caused by the fungus *Macrophomina phaseolina*, has been reported in crops such as sorghum and maize during drought periods [182]. These fungi have developed survival mechanisms that enable them to thrive in extreme

heat conditions within dry soil and subsequently migrate towards their target plants. Another fungus, *Aspergillus flavus*, has been implicated in causing premature growth and size reduction in drought-tolerant crops, while fungi from the genera *Fusarium* and *Bipolaris* have been associated with dryland foot and root rot, respectively [182].

In addition to diseases, toxic compounds have also been reported in drought tolerant crops meant for livestock feed implicated as the major causes of decreased survival rate of these plants. Groundnut shell from *Arachis hypogea* (L.) has been observed to accumulate aflatoxin contaminant, as investigated by [183], through subjecting the seeds to drought intense conditions. The study concluded that the drought tolerant ability of groundnut seeds does not help alleviate aflatoxin concentrations, posing a threat to livestock health. Drought resistant sorghum is also considered to be vulnerable to mycotoxin accumulation as analysis of 1533 samples revealed that a portion of 33% contained alarming levels of fumonisins, zearalenone, sterigmatocystin, *Alternaria* toxins and aflatoxins [184]. Additionally, factors such as sorghum color, collection period, source and country of origin were seen to significantly contribute to the type, amount and the spread of the analyzed mycotoxins [184]. The rationale behind drought tolerant crops being susceptible to mycotoxins, especially aflatoxins, can be explained by the climatic conditions of drought, which are extremely hot temperatures and heat stress, that support the growth of mycotoxigenic fungi. Existing edaphoclimatic conditions, characterized by low water availability, reduced nitrogen levels, poor soil quality, and increased toxic metal accumulation, contribute to oxidative stress, phosphate starvation and salt stress, ultimately disrupting the survival, nutrition, and growth of plants [185].

Ultimately, the noted diseases and accumulation of mycotoxins compromise feed safety standards which lead to limited applications of drought tolerant crops as alternative feed sources during feed scarcity. The appearance of pathogenic fungi and bacteria in a silage increases the risk of disease transmission to the livestock, consequently affecting the health of livestock and livestock product quality [186]. Institutions such as FAO and International Feed Industry Federation strongly recommend the application of proper storage, preservation and packaging techniques since they hold a valuable position in determining the final quality of the produced feed [187]. Despite silage being a common practice to produce feed for livestock, the silage method, however, has been reported as the main host of pathogenic microorganisms, especially when poorly monitored and managed [186]. Frequently occurring disease-causing microorganisms in silage are predominantly *Listeria*, *Salmonella enterobacteria* and *Clostridium* spp [186]. When silage is subjected to high amounts of moisture, *Clostridium* spp species bacteria develop and convert available carbohydrates into butyric acid instead of lactic acid leading to ketosis that can decrease milk production and weight gain in lactating cows [188]. Thus, when the safety of livestock feed is compromised, it poses health risks not only to the livestock themselves but also to the individuals who consume their products.

6.2. Low Crude Protein Content

CP amount is a critical nutritional element for livestock feed as it is crucial for nearly all biological processes in humans and livestock [189,190]. CP is a vital feed ingredient for efficient growth performance, tissue repair, milk production, weight gain, and ME, to name a few [191–193]. As a result of its implications in these crucial functions, minimum concentration of CP in livestock feed has been established. For ruminants, the minimum CP required is reported to be around 7.5%, lower concentrations than that are not advised since they may compromise rumen fermentation [194]. With lactating cows, a diet is recommended to contain about 160 g/kg CP in order to achieve metabolizable protein and reduced nitrogen excretion [198]. In bird husbandry, according to the veterinary manual, CP requirements for broiler rearing ranges from 18-23%, depending on the type and age of a bird fed. Using a fitting model, CP requirement was estimated to be around 21% for Jint Tint chicks during a six-week rearing period [55]. For laying hens to achieve desired egg production, CP should be 0.18 g CP/g egg mass [199]. Recently developed CP standards contain contents of 14.7, 22.7 and 35% for swine, poultry and fish feed evaluation, respectively [200]. These studies cite the

importance of a feed source to contain sufficient amounts of CP as part of the recommended dietary attributes, highlighting the point that elevated CP is indeed desirable for livestock nutrition.

However, as reported in Table 3, various studies have shown that a number of drought tolerant crops meant for livestock feed might fail to meet the minimum requirement for CP content due to the effects of drought and antinutritional compounds, such as tannins, that affect protein synthesis. Nutritional profiles of sorghum varieties (Pant Chari 5, PKV 809 and CSV 17) revealed low CP content (45.3 g/kg) Pant Chari 5 which expressed a decline in IVDMD [201]. *In vivo* analytical measurements also exhibited low CP intake when sheep were fed Pant Chari 5 variety. In other studies, it has been revealed that millets are also characterized by low protein content (7.2-7.8%). Pearl millets have been revealed to have low quantities of tryptophan and lysine, which are key amino acids that contribute to protein content [202]. Recent nutritional analysis of millet varieties proved finger millet contains the lowest CP of 7.24%, similarly little and kodo millets exhibited respective protein values of 7.6 and 7.8%, making their utilization limited only to ruminants at the minimal CP content highlighted above [202]. Varieties of sweet potato tubers of have been proven to contain CP range of 4-6% on DM basis which can be attributed to the occurrence of trypsin inhibitors [203]. *Ensete ventricosum* tuber revealed CP of 3.33% while the whole plant was reported to contain about 5.98% [8].

These findings suggest the need to blend drought tolerant crops with conventional livestock feed that contain high CP content. For example, supplementation of finger millet straw with various proportions of noug seed cake resulted in improved body weight gain compared to the control that contained finger millet straw only [195], emphasizing the need of protein supplementation in crops such as finger millet. A substitution of rice bran with 9% cassava generated a ruminant meal with approximately 14% CP in DM plus a better protein intake [196]. Likewise, *Opuntia ficus-indica* peel and 12% wheat bran yielded approximately 12% CP in DM [197]. Other approaches include adding fermenting microorganisms to low CP containing drought tolerant crops, as detailed in a recent review by [47] that the supplementation of *Trichoderma viride*, *Aspergillus niger* and *Saccharomyces cerevisiae* increased CP content in pineapple residues observed from various studies. These studies further demonstrate the importance of feed processing techniques like fermentation and ensiling which can be employed to optimize and enrich the CP in drought tolerant crops.

Table 3. Protein content of some of the drought tolerant crops used in livestock husbandry.

Alternative feed source	Crude protein (% DM)	Targeted livestock	References
Prickly pear silage	3.8	Ruminants	[55]
PT1ecotype <i>Opuntia ficus-indica</i> cladodes	6.9	N/A	[56]
PT5ecotype <i>Opuntia ficus-indica</i> cladodes	6.8	N/A	[56]
Winter <i>Opuntia ficus-indica</i>	4.15	Ruminants	[57]
Summer <i>Opuntia ficus-indica</i>	4.19	Ruminants	[57]
Sundried cassava peel meal	3.66	N/A	[58]
Pineapple residue	6	Holstein cows	[59]
Pineapple waste silage	6.2	Myanmar local cattle	[60]
Winter <i>Agave Americana</i> L	5.16	Ruminants	[57]
Summer <i>Agave Americana</i> L	6.30	Ruminants	[57]

N/A = Not Applicable. Note: The units are from the studies by Gebremariam et al. [61]; Degu et al. [62] and Rodrigues et al. [56] have been converted to % DM for uniformity as stipulated.

6.3. High Lignin Content and Limited Digestibility

The survival strategy of drought-tolerant crops, which primarily relies on high lignin composition to conserve water during periods of aridity, adversely affects feed digestibility by enzymes and the gut microbiome in livestock [207]. Although lignin is a necessary cell wall

component whose function is needed during hot temperatures, heat stress, transportation of minerals and mechanical support [208], its presence becomes a physical barrier hindering microbiome from reaching needed polysaccharides, cellulose, hemicellulose, starch and protein. The chemical make-up of lignin determines its digestibility. Lignin chemical composition includes two major monolignols (Figure 7): dimethoxylated syringyl (S) and monomethoxylated guaiacyl (G). As a result, the ability of these monolignols to form bonds with other units is directly related to a measured indigestibility of plant material in livestock. An increased concentration of G units is believed to enhance plant indigestibility, which may also be associated with greater maturity. It should be noted that lignin and plant digestibility are complex and challenging phenomena as lignin varies across plant species, also the method to measure the influence of lignin on digestibility cannot be easily applied due to various factors such as crop age, environmental conditions and plant morphology, to name a few [207].

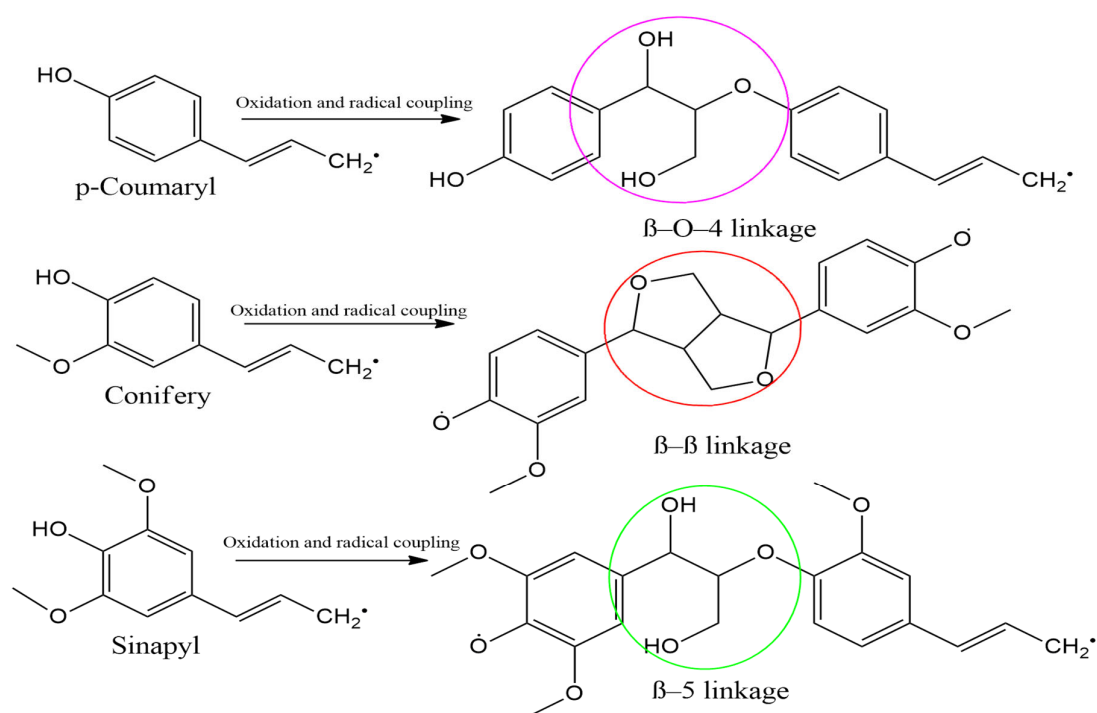


Figure 7. Lignin biosynthesis from phenylpropanoid units (p-coumaryl, coniferyl and sinangyl) resulting in bonds that restrict digestion. Created using Chemdraw.

The inability of rumen bacteria to efficiently degrade lignified plant cell wall limits the conversion of cellulose and hemicellulose to short fatty acids which play a crucial role in energy provision for livestock whereby lignin itself contains energy that is 30% higher than cellulose [207]. Highly lignified feed formulations extend the passage time of feed within the ruminal digestive system, thereby reducing feed intake. This reduction in feed intake can be correlated with poor feed quality and suboptimal livestock performance. The influence of lignin on feed digestibility has been extensively researched over the years, with various studies demonstrating a negative correlation between lignin concentration and digestibility [209–211]. For instance, increasing lignin concentration (9.59-13.3%, NDF basis) in feed diets reduced the digestibility of NDF, CP, and starch in lactating cows [212]. Supporting the notion that feed digestibility may also depend on the digestive system of the livestock, an *in vivo* study involving buffalo demonstrated excellent ADL degradability, presumed to be facilitated by microorganisms such as *Rikenellaceae* RC9 gut group, *Ruminococcaceae* UCG-011 and *Prevotella*1, 226 [213]. The extent to which the lignin undergoes degradation and affects digestibility may also depend on its structural composition, specifically highlighting which subunit

predominates. Feeds with a high presence of the sinapyl unit exhibited enhanced digestibility of ADF, NDF, and cellulose, suggesting that the linearity of sinapyl promotes efficient lignin degradation [214].

High concentrations of lignin and their detrimental effects on feed digestibility of drought tolerant crops have led to the development of pretreatment techniques aimed at reducing or removing lignin to make cellulose and hemicellulose more accessible for gut microbiota [215–217]. Several authors have reported on methods to lower lignin concentrations specifying pretreatments such as comminution, application of rot fungi, the use of chemicals such as potassium hydroxide, sodium hydroxide, calcium hydroxide, sulphuric acid and physical pretreatments such as soaking and mechanical grinding [218]. Escapa et al. [219] and Jędrzejczyk et al. [217] have further reported on the use of grinding, pyrolysis (using temperature greater than 300°C), microwave oven, hot water, acid or alkaline pretreatment. Pretreatments created from enzymatic systems are also reported as a viable option able to decrease lignin content in livestock feed [220]. The common objective of these cited pretreatment applications is to disrupt the cross-links present in lignocellulosic compounds to facilitate the availability of essential nutrients, such as sugar polymers, for further efficient digestion in livestock.

6.4. Socio Economic and Financial Challenges

The adoption of drought tolerant crops faces several interconnected challenges. These include insufficient knowledge and training, lack of awareness, limited availability support from extension services, restricted access to improved seed varieties, limited land for food production, and lack of capital for investment.

Livestock owners in arid regions lack the necessary knowledge needed in order to fully understand the implications of drought tolerant crops in livestock feed systems. For example, in Uganda, it has been reported that the limited adoption of drought tolerant crops by smallholder farmers included lack of awareness about the crops which further resulted in low crop production [221]. With respect to the cacti plants, farmers are unaware of the difference between spiny and spineless cactus, leading to the perception that both plants are the same [222]. Meanwhile, in some areas like Pakistan the cultivation of cacti species is not valued as it is perceived that they are invasive species, rendering their farming fruitless. This perception highlights the lack of awareness, knowledge and training on the use of drought tolerant crops, for smallholder farmers. The use of drought tolerant crops for livestock forms part of the climate smart agricultural approach, however, the use of climate smart approaches is hindered by insufficient technical knowledge amongst smallholder farmers [223].

The access to technical information is one of the challenges facing the extended use of drought tolerant crops in livestock feed. Research results from drought tolerant crops fail to reach the ultimate beneficiaries. For instance, limited access to improved seed systems for enhanced sorghum varieties by smallholder farmsteads in regions such as Nigeria has been reported [224]. Besides limited access to research information, the available engineered or certified seeds are more expensive compared to the traditional ones [225]. Acevedo et al. [226] reported that both access and lack of information on the certified seed varieties were principal barriers that hindered farmers from adopting climate resilient crops, especially those with low-income status. These findings underscore a lack of support from agricultural extension services, whose duties include providing support, guidance and information to local farmers.

Another significant barrier to using drought-tolerant crops for livestock feed is the limited land for food production. This challenge is further intensified by water scarcity, land degradation and arability, which limit the resources available for sustainable feed crop cultivation. For instance, South African arable land is only about 12% of the total surface area while the rest is considered for grazing [227]. Unfavorable edaphoclimatic variations are reported to contribute to the observed limited land use for crop production, allowing the irrigation of rain fed crops only. Lack of capital and monetary support from financial institutions is also hindering the adoption of climate smart agriculture

practices, especially for small-medium scale farmers. Olabanji et al. [228] reported that smallholder farmers in South Africa often face challenges in accessing credit from financial organizations, limiting their participation in climate smart agriculture interventions. Addressing these issues requires increased investment and support systems to encourage the use of these crucial crops, ensuring food security and sustainable agricultural practices.

7. Key Strategies for Sustainable Innovation for Drought Tolerant Livestock Feed

7.1. Increased Awareness

To effectively address the challenge of limited awareness regarding the adoption of drought-tolerant crops, relevant organizations and institutions (across private, non-governmental, and government sectors) need to establish strong relationships with smallholder farmers in rural settlements. Awareness campaigns and outreach programs, especially in rural farmsteads, are important to strengthen and yield increased adoption of drought-tolerant crops in arid environments. The outreach programs should focus on informing the farmers about available agricultural extension services, knowledge on climate-smart technology, where and how to access drought-resilient certified seeds, the latest research findings, financial support, and the importance of drought-tolerant crops as livestock feed [226]. Partnerships with key stakeholders such as telecommunication companies, government, and non-governmental organizations will help facilitate the awareness and widespread adoption of drought-resilient plants in livestock [226]. Zougmore et al. [229] emphasized the need to increase awareness of climate-smart technologies, especially for vulnerable communities. In some parts of Southern Africa (Zimbabwe and South Africa), there is evident lack of awareness of drought tolerant crops as a climate smart agriculture for improved crop production. The adoption of drought resilient maize varieties by smallholder farmers has shown increased crop yield compared to those who did not cultivate these varieties [230,231]. Furthermore, their incorporation resulted in increased profits of US\$240/ha with no additional cost incurred. This is proof that continuous awareness programs with a specific focus on the adoption of drought tolerant crops for livestock feed hold a potential that can help improve the performance of livestock in arid regions. This approach will help to disseminate information about climate-resilient plants and their implications in livestock productivity to help small-scale farmers to make informed decisions.

7.2. Policy Reforms

Policies supporting innovation in drought-tolerant crops for livestock feed are crucial as a vehicle that will allow small-scale farmers to access the needed financial support, research and development, and regulatory frameworks. Besides, reforming the existing policies is further needed to ensure inclusion and widespread adoption of drought resilient crops as climate smart agriculture in smallholder farming operations, especially livestock producers. The current policies are reported to be unfavorable for small-scale livestock producers, especially in African countries [232]. Acevedo et al. [226] purported that the existing seed policies have created challenges in accessing the improved seed varieties by the majority of farmers. Wongnaa [232] stresses that for livestock farms to be sustainable during unpredictable climatic events, policy reforms must be prioritized. On the other hand, Ghana and Nigeria have successfully developed policies planned at implementing climate-smart agricultural practices for farmers vulnerable to drought [229,233]. In Mali, policy reforms have enabled the implementation and provision of eco-friendly solutions, such as bio-pesticides, organic fertilizers, fallow and zero tillage, as part of climate change adaptation strategies [234]. Although these examples support the notion that inclusion of drought-resilient crops for livestock feed during policy reform is possible, there is an urgent need for the development of policies that support and prioritize innovation of drought-tolerant crops for livestock feed.

Policy frameworks also need to promote financial support for farmers interested in the production and processing of drought tolerant crops for livestock feed. This is critical to help the

farmers to afford the machinery needed and land for the planned projects [232]. For instance, FAO, in collaboration with the Canadian government, introduced a project that financially supports smallholder farmers to afford certified seeds of drought tolerant fodder, livestock breeding tools and equipment [228]. In addition, government investment in research on innovation of drought tolerant crops in livestock feed is fundamental to developing new, higher-yielding, and nutritious drought tolerant varieties suitable for local conditions. This includes utilizing advanced techniques such as molecular breeding and gene-editing tools. Public-private partnerships, such as the Drought Tolerant Maize for Africa program, an initiative led by International Maize and Wheat Improvement Center and the International Institute of Tropical Agriculture, with an aim to develop and distribute drought-tolerant maize varieties in sub-Saharan Africa is one good example of a successful model for future initiatives. Such models are also needed for innovations that focus on livestock feed, ensuring that policy interventions adequately support innovation in drought tolerant crops for livestock feed.

7.3. Strengthening of Research Capacity

Strengthened research, integrating traditional breeding with cutting-edge biotechnology such as marker-assisted selection and gene editing, is vital to accelerate the development and use of superior drought-tolerant varieties. Research on Sudan sorghum has proven that genetic manipulation, through traditional breeding techniques, is able to produce varieties with optimized growth abilities as it can be propagated in various soil types without the loss of its nutritional value. Research on cultivar breeding of forages is an ideal approach to improve plant resistance, durability and nutritional value of the crops of interest [235], *Lolium*, *Trifolium* and *Medicago* spp are crops that have shown greatest improvements through breeding technology [235]. The continuous research on these species has attracted the participation of various institutes across Canada and United States, showcasing how joint cooperative efforts improve the quality of research findings that benefit both research and industry. Similar plant breeding projects exist in countries such as Uganda, Tanzania and Mozambique which aim to explore ways to improve crop varieties for livestock feed [236].

Despite advancements in research on drought-tolerant crops, a significant disconnect persists among academia, industry, and government, hindering support for research into these crops as alternative feed sources during droughts. This gap is particularly evident in South Africa, where research on alternative feed and superior forage options is limited [5], and public evidence of collaboration between the government and the private sector is lacking. Although industry and government maintain active breeding programs, academic involvement is less common. Consequently, research institutions contribute minimally to generating the data needed to encourage the wider adoption of drought-tolerant crops among smallholder farmers. By increasing governmental funding for academic research, scientists can create the essential tools needed to help small farmsteads transition to using drought-tolerant feed crops. Thus, collaboration among researchers, government, industry, and farmers is an effective way to optimize the use of drought-tolerant crops for animal feed, which is becoming increasingly important due to unpredictable climate change. Crucially, research investments focused on enhancing the quality, processing efficiency, shelf life, and overall quantity of alternative feed sources (drought-tolerant crops) will boost their adoption by small-scale farmers.

8. Conclusions and Prospects

This review critically discussed the role of key drought-tolerant crops —including *Sorghum bicolor*, *Pennisetum glaucum*, *Manihot esculenta*, *Ensete ventricosum*, and *Opuntia ficus-indica* — as alternative livestock feed. It highlighted the main drivers for the use of drought-tolerant crops and provided an in-depth discussion on their processing and application, factors influencing their quality, challenges, and strategies to promote their innovation as climate smart agriculture strategy. The impact of climate change is the main driver for the application and research of drought-tolerant crops for livestock feed as climate unpredictability continues to threaten traditional feed resources and livestock productivity. Various techniques such as drying, ensiling, milling, and pelleting have been

applied to process drought-tolerant crops. Sun drying is still the predominant method for drying drought-tolerant crops, and there is a noticeable absence of advanced drying techniques, indicating a need for research and innovation in this field. The incorporation of alternative feedstuffs such as *Sorghum bicolor*, *Pennisetum glaucum*, *Manihot esculenta*, *Ensete ventricosum*, and *Opuntia ficus-indica* into livestock diets to partially or wholly replace conventional feed has shown promising results in enhancing animal health and nutrition. However, optimizing these formulations is essential for achieving the best outcomes. Cultivar and maturity stage are the main preharvest factors affecting the quality of drought tolerant crops and their livestock feed, whilst after harvesting, drying, grinding and pulverization, ensiling and storage processes are the key determinants of quality preservation and enhancement. There is a need for further research to comprehensively study these crucial quality determinants, especially how they interact with each other and across a diverse range of drought-tolerant crops.

The development of drought-tolerant crops faces several key challenges, including susceptibility to disease and mycotoxins, low protein levels, and issues with digestibility due to high lignin content. Socio-economic and financial obstacles also limit their effectiveness. To fully leverage the potential of these crops for food and nutrition security and climate-smart agriculture, a comprehensive, integrated strategy is necessary to address all these issues. While progress is being made in developing drought-tolerant crops, several key research areas remain under-explored. Firstly, there is a need to expand research on various drought tolerant crops as the current research focuses on a limited number of crops mainly, *Sorghum bicolor*, and *Pennisetum glaucum* which are crops for human food. Though research has expanded to other drought-tolerant crops like *Opuntia ficus-indica* species, this particular crop's vast potential as a solution to livestock feed shortages in drought-prone areas remains entirely underutilized. Current research on *Opuntia ficus-indica* has primarily focused on the nutritional profiling of the whole cladodes, despite the plant's overall importance and potential of fruit waste. This approach overlooks the potential for significant nutritional and techno-functional differences in specific components of cladodes like mucilage and fiber, which could greatly influence the properties of feed derived from cladodes. Additionally, studies lack diversity in investigating the influence of cultivar and maturity stage. Although the *Opuntia ficus-indica* is globally distributed, research is geographically sparse. Addressing these critical factors is essential for driving innovation related to this plant. While advanced drying methods such as freeze-drying are not commonly used, they remain critical as the gold standard for preservation. This benchmark is essential for assessing the impact of other processing techniques and underscores the necessity of advanced technology in developing drought-tolerant crops.

The short-term future research strategies for innovating drought tolerant crops for livestock feed should focus on: 1.) identifying more drought tolerant species, optimizing agronomic and water management practices, as well as intensifying research on preharvest and processing factors 2.) application of inorganic and organic nutrients and chemicals to support their growth or enhance the drought resistance and antioxidant defense systems, 3.) policy and financial support, 4.) integrated research platforms, 5.) create more awareness on the potential of the drought tolerant crops as sustainable livestock feed, 6.) carry out techno economic and environmental impact of producing drought tolerant crops and processing them into feed. Meanwhile, the long-term future research strategies should focus on 1.) advanced plant breeding and genetic engineering, and 2.) exploring novel drought tolerant crops. Bulleted lists look like this:

Author Contributions: S.T and T.K: Conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization; J.O.A: writing—review and editing; supervision; N.M: writing—review and editing, funding acquisition; O.A.F: project administration, funding acquisition, supervision.

Funding: The funding of this work is provided by the South African National Department of Agriculture, Land Reform and Rural Development (DALRRD).

Data Availability Statement: No data was generated in this review article.

Acknowledgments: This work is based on research supported by the National Research Foundation of South Africa (SPAR231013155231), the University Research Committee at the University of Johannesburg (UJ). The opinions, findings, and conclusions or recommendations expressed are those of the authors alone, and the NRF, UJ, and DALRRD accept no liability whatsoever in this regard.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

ADF	Acid detergent fiber
ADL	Acid detergent lignin
BMR	Brown midrib
CAM	Crassulacean acid metabolism
CP	Crude protein
DM	Dry matter
CAM	Dry matter yield
DPPH	2,2-diphenyl-1-picrylhydrazyl
FAO	Food and agricultural organization
FCR	Feed conversion ratio
GAE	Gallic acid equivalent
GE	Gross energy
IVOMD	In vitro organic matter digestibility
LAB	Lactic acid bacteria
ME	Metabolizable energy
MRSA	Methicillin resistant Staphylococcus aureus
NDF	Neutral detergent fiber
OAA	Oxaloacetic acid
OM	Organic matter
ORAC	Oxygen radical absorbance capacity
PEP	Phosphoenol pyruvate
SDDGs	Soluble dried distiller's grains
SW	Sweet sorghum
WUE	Water use efficiency

References

1. Boyomo HAA, Nkoa BEO, Manga LAA. Climate change and livestock production in Sub-Saharan Africa: Effects and transmission channels. *Food Energy Secur* 2024;13:521. <https://doi.org/https://doi.org/10.1002/fes3.521>.
2. Herrero M, do Valle CB, Hughes NRG, et al. Measurements of physical strength and their relationship to the chemical composition of four species of Brachiaria. *Anim Feed Sci Technol* 2001;92:149–58. [https://doi.org/10.1016/S0377-8401\(01\)00261-9](https://doi.org/10.1016/S0377-8401(01)00261-9).
3. Salmon GR, MacLeod M, Claxton JR, et al. Exploring the landscape of livestock 'Facts.' *Glob Food Sec* 2020;25:100329. <https://doi.org/10.1016/j.gfs.2019.100329>.
4. Makkar HPS. Review: Feed demand landscape and implications of food-not feed strategy for food security and climate change. *Animal* 2018;12:1744–54. <https://doi.org/10.1017/S175173111700324X>.
5. Mbambalala L, Rani ZT, Mpanza TDE, et al. Fodder Radish as a Potential Alternative Feed Source for Livestock in South Africa. *Agriculture* 2023;13:1625. <https://doi.org/10.3390/agriculture13081625>.
6. Alimi N, Assani AS, Sanni Worogo H, et al. Livestock feed resources used as alternatives during feed shortages and their impact on the environment and ruminant performance in West Africa: a systematic review. *Front Vet Sci* 2024;11. <https://doi.org/10.3389/fvets.2024.1352235>.
7. Islami RZ, Utomo D, Budiawati Y, et al. Potential of agricultural by-products and waste as ruminant animal feed : A systematic literature review 2025. <https://doi.org/10.21203/RS.3.RS-6028478/V1>.
8. Mohammed B, Martin G, Laila MK. Nutritive values of the drought tolerant food and fodder crop enset. *Afr J Agric Res* 2013;8:2326–33. <https://doi.org/10.5897/AJAR12.1296>.

9. Nguyen V, Riley S, Nagel S, et al. Common Vetch: A Drought Tolerant, High Protein Neglected Leguminous Crop With Potential as a Sustainable Food Source. *Front Plant Sci* 2020;11. <https://doi.org/10.3389/fpls.2020.00818>.
10. Shaffril MHA, Samah AA, Samsuddin SF, et al. Diversification of agriculture practices as a response to climate change impacts among farmers in low-income countries: A systematic literature review. *Clim Serv* 2024;35:100508. <https://doi.org/10.1016/j.cliser.2024.100508>.
11. Balogun BI, Omodara AA, Owoyele OO. Effects of sun-dried cassava peels on growth performance in Red Sokoto does (*Capra aegagrus hircus*) during gestation. *Sci World J* 2025;19:1062–7. <https://doi.org/10.4314/swj.v19i4.22>.
12. da Silva AEM, Macias Franco A, Solomon JKQ, et al. Cactus (*Opuntia ficus-indica*) diets reduce voluntary water intake, water footprint and enteric methane production improving ruminal fermentation in steers. *J Arid Environ* 2025;227:105311. <https://doi.org/10.1016/j.jaridenv.2024.105311>.
13. Hafeni-Shihepo S. Production performance of broiler chickens fed mash and pelleted pearl millet-based diets. *S Afr J Anim Sci* 2025;54:575–82. <https://doi.org/10.4314/sajas.v54i5.04>.
14. Pontieri P, Del Giudice L, Masucci F, et al. The potential of sorghum meal as a replacement of corn meal in the diet for lactating buffaloes: impacts on milk yield and nutrient digestibility. *Ital J Anim Sci* 2025;24:1415–26. <https://doi.org/10.1080/1828051X.2025.2519824>.
15. Shavazov K, Mamatkulov R, Tursunov S, et al. Addition of sorghum grain to broiler chicken diets and its effect on productivity and safety. *BIO Web Conf* 2025;161:00066. <https://doi.org/10.1051/bioconf/202516100066>.
16. Godde CM, Mason-D’Croz D, Mayberry DE, et al. Impacts of climate change on the livestock food supply chain; a review of the evidence. *Glob Food Sec* 2021;28:100488. <https://doi.org/10.1016/j.gfs.2020.100488>.
17. Klinck L, Ayisi KK, Isselstein J. Drought-induced challenges and different responses by smallholder and semicommercial Livestock farmers in semiarid Limpopo, South Africa—An indicator-based assessment. *Sustainability* 2022;14:8796. <https://doi.org/10.3390/su14148796>.
18. Sintayehu DW, Alemayehu S, Terefe T, et al. Effects of Drought on Livestock Production, Market Dynamics, and Pastoralists’ Adaptation Strategies in Semi-Arid Ethiopia. *Climate* 2025, Vol 13, Page 65 2025;13:65. <https://doi.org/10.3390/CLI13040065>.
19. Puerto Rico Department of Agriculture SD. Summary of the agricultural losses during the 2015 Drought. San Juan, Puerto Rico 2017.
20. Marsland N. 2015-2016 El Niño Early Action and Response for Agriculture, Food Security and Nutrition. United Nations Human Settlements Programme (UN-Habitat): Addis Ababa, Ethiopia (2021) 2016:52.
21. Ainembabazi JH. The 2015-16 El Niño-induced drought crisis in Southern Africa: What do we learn from historical data?, International Association of Agricultural Economists; 2018. <https://doi.org/https://doi.org/10.22004/ag.econ.275952>.
22. Ewbank R, Perez C, Cornish H, et al. Building resilience to El Niño-related drought: experiences in early warning and early action from Nicaragua and Ethiopia. *Disasters* 2019;43:S345–67. <https://doi.org/10.1111/DISA.12340>.
23. Júnior R de SN, Sentelhas PC. Soybean-maize off-season double crop system in Brazil as affected by El Niño Southern Oscillation phases. *Agric Syst* 2019;173:254–67. <https://doi.org/10.1016/j.agsy.2019.03.012>.
24. Abebe M. Evaluation of replacing wheat bran with Ensete *Ventricosum* Corm on feed intake, weight gain, in vitro digestibility and economic efficiency of Doyogena sheep [Masters’ degree thesis]. Wachemo University, 2024.
25. Fang Y, Xiong L. General mechanisms of drought response and their application in drought resistance improvement in plants. *Cell Mol Life Sci* 2015;72:673–89. <https://doi.org/10.1007/s00018-014-1767-0>.
26. Thabet SG, Alqudah AM. Crops and Drought. *Encyclopedia of Life Sciences*, Wiley; 2019, p. 1–8. <https://doi.org/10.1002/9780470015902.a0025265>.
27. Wang X, Li X, Zhao W, et al. Current views of drought research: experimental methods, adaptation mechanisms and regulatory strategies. *Front Plant Sci* 2024;15. <https://doi.org/10.3389/fpls.2024.1371895>.
28. Pamungkas SST, Farid N. Drought stress: Responses and mechanism in plants. *Rev Agric Sci* 2022;10:168–85. https://doi.org/10.7831/ras.10.0_168.

29. Shavrukov Y, Kurishbayev A, Jatayev S, et al. Early flowering as a drought escape mechanism in plants: How can it aid wheat production? *Front Plant Sci* 2017;8:302418. <https://doi.org/10.3389/FPLS.2017.01950/BIBTEX>.
30. Panda D, Mishra SS, Behera PK. Drought tolerance in rice: Focus on recent mechanisms and approaches. *Rice Sci* 2021;28:119–32. <https://doi.org/10.1016/j.rsci.2021.01.002>.
31. Aslam M, Maqbool MA, Cengiz R. Mechanisms of drought resistance. In *drought stress in maize (Zea mays L.) effects, resistance mechanisms, global achievements and biological strategies for improvement*, Springer, Cham; 2015, p. 19–36. https://doi.org/10.1007/978-3-319-25442-5_3.
32. Yang X, Cushman JC, Borland AM, et al. A roadmap for research on crassulacean acid metabolism (CAM) to enhance sustainable food and bioenergy production in a hotter, drier world. *New Phytol* 2015;207:491–504. <https://doi.org/10.1111/nph.13393>.
33. Gilman IS, Edwards EJ. Crassulacean acid metabolism. *Curr Biol* 2020;30:R57–62. <https://doi.org/10.1016/j.cub.2019.11.073>.
34. Ghannoum O. C₄ photosynthesis and water stress. *Ann Bot* 2008;103:635–44. <https://doi.org/10.1093/aob/mcn093>.
35. Ronda V, Aruna C, Visarada KBRS, et al. Sorghum for animal feed. In *Breeding sorghum for diverse end uses*, Elsevier; 2019, p. 229–38. <https://doi.org/10.1016/B978-0-08-101879-8.00014-0>.
36. Manole D, Giumba AM, Ganea L. Sorghum, an alternative in complementarity with corn, adapted to climate changes. Amzacea Village, Constanta County, Romania. *Sci Pap Ser Manag Econ Eng Agric Rural Dev* 2023;23:501-512.
37. Lara MV, Andreo CS, Lara MV, et al. C₄ Plants Adaptation to High Levels of CO₂ and to Drought Environments. *Abiotic Stress in Plants - Mechanisms and Adaptations* 2011. <https://doi.org/10.5772/24936>.
38. Crush JR, Rowarth JS. The role of C₄ grasses in New Zealand pastoral systems. *NZ J Agric Res* 2007;50:125–37. <https://doi.org/10.1080/00288230709510287>.
39. Shah WH, Saleem S, Mushtaq NU, et al. C₄ and CAM plants with better resilience to environmental stresses. In *Photosynthesis and Respiratory Cycles during Environmental Stress Response in Plants*, Apple Academic Press; 2022, p. 163–91. <https://doi.org/10.1201/9781003315162-8>.
40. Taylor JRN. Sorghum and millets: Taxonomy, history, distribution, and production. In *Sorghum and Millets*, AACC International Press; 2019, p. 1–21. <https://doi.org/10.1016/B978-0-12-811527-5.00001-0>.
41. Lima R, Lourenço M, Díaz RF, et al. Effect of combined ensiling of sorghum and soybean with or without molasses and lactobacilli on silage quality and in vitro rumen fermentation. *Anim Feed Sci Technol* 2010;155:122–31. <https://doi.org/10.1016/j.anifeeds.2009.10.008>.
42. Langdale JA. C₄ cycles: past, present, and future research on C₄ photosynthesis. *Plant Cell* 2011;23:3879–92. <https://doi.org/10.1105/tpc.111.092098>.
43. Yang X, Liu Y, Yuan G, et al. Engineering Crassulacean Acid Metabolism in C₃ and C₄ Plants. *Cold Spring Harb Perspect Biol* 2023;a041674. <https://doi.org/10.1101/cshperspect.a041674>.
44. Lüttge U. Ability of crassulacean acid metabolism plants to overcome interacting stresses in tropical environments. *AoB Plants* 2010;2010. <https://doi.org/10.1093/aobpla/plq005>.
45. Zea LS, Uribe JAG, Saldivar SOS. Comparative analyses of total phenols, antioxidant activity, and flavonol glycoside profile of cladode flours from different varieties of *Opuntia* spp. *J Agric Food Chem* 2011;59:7054–61. <https://doi.org/10.1021/jf200944y>.
46. Pastorelli G, Serra V, Vannuccini C, et al. *Opuntia* spp. as Alternative Fodder for Sustainable Livestock Production. *Animals* 2022;12:1597. <https://doi.org/10.3390/ani12131597>.
47. Sukri SAM, Andu Y, Sarijan S, et al. Pineapple waste in animal feed: A review of nutritional potential, impact and prospects. *Ann Anim Sci* 2023;23:339–52. <https://doi.org/10.2478/aoas-2022-0080>.
48. Gusha J, Halimani TE, Katsande S, et al. The effect of *Opuntia ficus indica* and forage legumes based diets on goat productivity in smallholder sector in Zimbabwe. *Small Ruminant Research* 2015;125:21–5. <https://doi.org/10.1016/j.smallrumres.2015.02.018>.
49. Hassan S, Louhaichi M. Cactus Pear: A multipurpose crop and resilient feed source in dry environments. *Accel-erated Breeding Initiative (ABI) Forage Germplasm Selection and Breeding*, Rome, Italy: 2023.

50. Jacobo MC, González PS. Cactus (*Opuntia Spp.*) as Forage - Food and Agriculture Organization of the United Nations - Google Books. vol. 169. Food and Agriculture Org; 2001.
51. Yamori W, Hikosaka K, Way DA. Temperature response of photosynthesis in C3, C4, and CAM plants: temperature acclimation and temperature adaptation. *Photosynth Res* 2014;119:101–17. <https://doi.org/10.1007/s11120-013-9874-6>.
52. Ran T, Fang Y, Wang YT, et al. Effects of grain type and conditioning temperature during pelleting on growth performance, ruminal fermentation, meat quality and blood metabolites of fattening lambs. *Animal* 2021;15:100146. <https://doi.org/10.1016/j.animal.2020.100146>.
53. Khalifa M, Eltahir EAB. Assessment of global sorghum production, tolerance, and climate risk. *Front Sustain Food Syst* 2023;7:1184373. <https://doi.org/10.3389/FSUFS.2023.1184373/XML/NLM>.
54. Yusriani Y, Ushrina N, Fitriawaty, et al. Potential and utilization of sorghum in dry land as animal feed. *IOP Conf Ser Earth Environ Sci* 2024;1297:012023. <https://doi.org/10.1088/1755-1315/1297/1/012023>.
55. Liu Y, Zhou Q, Ji C, et al. Microbial fermentation in co-ensiling forage-grain ratoon rice and maize to improve feed quality and enhance the sustainability of rice-based production systems. *Resources, Environment and Sustainability* 2025;20:100205. <https://doi.org/10.1016/J.RESENV.2025.100205>.
56. Segú H, Jalševac F, Pinent M, et al. Intestinal morphometric changes induced by a western-style diet in Wistar rats and GSPE counter-regulatory effect. *Nutrients* 2022;14:2608. <https://doi.org/10.3390/nu14132608>.
57. Hou Z, Yu X, Wu D. Effects of different ratio of sweet sorghum silage to corn silage diets on serum metabolome of lactating dairy cows. *Trop Anim Health Prod* 2025;57:229. <https://doi.org/10.1007/s11250-025-04483-8>.
58. Hassan ZM, Sebola NA, Mabelebele M. The nutritional use of millet grain for food and feed: a review. *Agric Food Secur* 2021;10:16. <https://doi.org/10.1186/s40066-020-00282-6>.
59. Gowda NKS, Prasad CS. Macro- and micro-nutrient utilization and milk production in crossbred dairy cows fed finger millet (*Eleusine coracana*) and rice (*Oryza sativa*) straw as dry roughage source. *Asian-Australas J Anim Sci* 2005;18:48–52. <https://doi.org/10.5713/ajas.2005.48>.
60. Girgiri A, Muhammad M, Kolo UM, et al. Evaluation of finger millet (*Eleusine coracana L.*) fodder production and utilization by dairy goats in a semi-arid environment of Nigeria. *J Arid Agric* 2024;25:110–6. <https://jaaunimaid.ng/index.php/home/article/view/32> (accessed December 9, 2025).
61. Sachin SS, Sanjay GC, Prabhu TM, et al. Comparative evaluation of extruded complete feeds based on finger millet (*Eleusine coracana*) straw, areca (*Areca catechu*) sheath and maize (*Zea mays*) cob in Mandya lambs. *Indian J Anim Res* 2023. <https://doi.org/10.18805/IJAR.B-5016>.
62. Mugula JK, Nnko SAM, Narvhus JA, et al. Microbiological and fermentation characteristics of togwa, a Tanzanian fermented food. *Int J Food Microbiol* 2003;80:187–99. [https://doi.org/10.1016/S0168-1605\(02\)00141-1](https://doi.org/10.1016/S0168-1605(02)00141-1).
63. Cisse RS, Hamburg JD, Freeman ME, et al. Using locally produced millet as a feed ingredient for poultry production in Sub-Saharan Africa. *J Appl Poul Res* 2017;26:9–22. <https://doi.org/10.3382/japr/pfw042>.
64. Kawu YU, Doma M, Abubakar K, et al. Performance and economics of production of broiler chickens fed dietary levels of gayamba pearl millet (*Pennisetum glaucum L.*) as replacement for red sorghum (*Sorghum bicolor*). *Nig J Anim Sci Technol* 2019;2:72–84. <https://njast.com.ng/index.php/home/article/view/25> (accessed December 9, 2025).
65. Oskey MA. Yield and nutritional composition of conventional and BMR pearl millet under different management conditions [Master's degree thesis]. Clemson University, 2020.
66. Sabo MN, Duru S, Afolayan SB. Carcass characteristics of Japanese quails (*Coturnix coturnix japonica*) fed whole or ground pearl millet (*Pennisetum glaucum*) with or without enzyme supplementation. *FUDMA J Sci* 2020;4:539–44.
67. Santos JW, Cabral L da S, Zervoudakis JT, et al. Finger millet grain levels in sheep diets: intake and digestibility. *Revista Brasileira de Zootecnia* 2008;37:1884–9. <https://doi.org/https://doi.org/10.1590/S1516-35982008001000024>.

68. Adegbeye MJ, Ravi Kanth Reddy P, Obaisi AI, et al. Sustainable agriculture options for production, greenhouse gasses and pollution alleviation, and nutrient recycling in emerging and transitional nations - An overview. *J Clean Prod* 2020;242:118319. <https://doi.org/10.1016/j.jclepro.2019.118319>.
69. Tong Y, Wu J, Guo W, et al. The effect of combining millet and corn straw as source forage for beef cattle diets on ruminal degradability and fungal community. *Animals* 2023;13:548. <https://doi.org/10.3390/ani13040548>.
70. Berhanu H, Kiflie Z, Miranda I, et al. Characterization of crop residues from false banana /*Ensete ventricosum*/ in Ethiopia in view of a full-resource valorization. *PLoS One* 2018;13:e0199422. <https://doi.org/10.1371/JOURNAL.PONE.0199422>.
71. Fekade AN. Replacement value of *Ensete Ventricosum* CORM AND Kocho for maize in broiler and layer ration [Doctoral dissertation]. Haramaya university, 2018.
72. OECD, FAO. OECD-FAO Agricultural outlook 2025-2034. *OECD-FAO Agricultural Outlook* 2025;2025. <https://doi.org/10.1787/601276CD-EN>.
73. Hang NTB, Doan CC. Improving nutrition facts of cassava and soybean residue through solid-state fermentation by *pleurotus ostreatus* mycelium: A pathway to safety animal feed production. *Ferment* 2025;11:271. <https://doi.org/10.3390/fermentation11050271>.
74. Rashid M, Aboshady HM, Soltan YA, et al. Phytochemical profile and in vitro evaluation of cassava (*Manihot esculenta* Crantz) foliage as ruminant feed with/without green banana flour. *Sci Rep* 2025;15:721. <https://doi.org/10.1038/s41598-024-82450-3>.
75. Triani HD, Yuniza A, Marlida Y, et al. Potential of fermented cassava peel and leaves as maize substitutes in diets to improve the performance and meat quality of Kamang ducks. *J Anim Feed Sci* 2025. <https://doi.org/10.22358/jafs/200810/2025>.
76. Ogbuewu IP, Mbajiorgu CA. Meta-analysis of substitution value of maize with cassava (*Manihot esculenta* Crantz) on growth performance of broiler chickens. *Front Vet Sci* 2022;9. <https://doi.org/10.3389/fvets.2022.997128>.
77. Abang FBP, Anoh KU, Izuki ED, et al. Productive performance and hematological indices of broiler chicks fed biodegraded cassava root. *Online Journal of Animal and Feed Research* 2023;13:274–8. <https://doi.org/10.51227/ojafr.2023.41>.
78. Gunun N, Phimda R, Piamphon N, et al. Effect of replacing concentrates with cassava root-top silage on feed utilization, rumen fermentation, blood parameters and growth performance in beef cattle. *Anim Biosci* 2024;37:1751–8. <https://doi.org/10.5713/ab.24.0076>.
79. Yang Y, Lei F, Zhang Z, et al. Effects of cassava root meal on the growth performance, apparent nutrient digestibility, organ and intestinal indices, and slaughter performance of yellow-feathered broiler chickens. *Trop Anim Health Prod* 2024;56:274. <https://doi.org/10.1007/s11250-024-04135-3>.
80. Gebremariam T, Melaku S, Yami A. Effect of different levels of cactus (*Opuntia ficus-indica*) inclusion on feed intake, digestibility and body weight gain in tef (*Eragrostis tef*) straw-based feeding of sheep. *Anim Feed Sci Technol* 2006;131:43–52. <https://doi.org/10.1016/j.anifeedsci.2006.02.003>.
81. Dubeux JCB, Santos MVF dos, Cunha MV da, et al. Cactus (*Opuntia* and *Nopalea*) nutritive value: A review. *Anim Feed Sci Technol* 2021;275:114890. <https://doi.org/10.1016/j.anifeedsci.2021.114890>.
82. Tafere G. Cactus pear, cladodes (*Opuntia ficus-indica*); as forage for livestock in arid and semi-arids of Ethiopia feeding under a changing climate—A review. *Int J Integr Sci Innov Technol* 2016;5:12–4.
83. Tegegne F, Kijora C, Peters KJ. Study on the optimal level of cactus pear (*Opuntia ficus-indica*) supplementation to sheep and its contribution as source of water. *Small Rumin Res* 2007;72:157–64. <https://doi.org/10.1016/j.smallrumres.2006.10.004>.
84. Salem BH, Smith T. Feeding strategies to increase small ruminant production in dry environments. *Small Rumin Res* 2008;77:174–94. <https://doi.org/10.1016/j.smallrumres.2008.03.008>.
85. Gebreegziabher Z, Tsegay B. Efficacy of cactus pear (*Opuntia ficus-indica*) varieties as a source of food and feed in Endamehoni district, northern Ethiopia. *Afr J Food Agric Nutr Dev* 2015;15:10406–27. <https://doi.org/10.18697/ajfand.72.14090>.

86. Gebremariam D, Machin D. Evaluation of sun dried sisal pulp (*Agave sisalana* Perrine) as feed for sheep in Eritrea. *Livest Res Rural Dev* 2008;20. <http://www.lrrd.org/lrrd20/11/gebr20183.htm> (accessed December 9, 2025).
87. Albuquerque I, Araújo G, Santos F, et al. Performance, body water balance, ingestive behavior and blood metabolites in goats fed with cactus pear (*Opuntia ficus-indica* L. Miller) silage subjected to an intermittent water supply. *Sustainability* 2020, Vol 12, Page 2881 2020;12:2881. <https://doi.org/10.3390/SU12072881>.
88. Badr SEA, Fattah MSA, Elsaid AS. Productive performance and meat quality of commercial Cobb chicken fed diets containing different levels of prickly pear fruits (*Opuntia ficus indica*) peel. *Bull Natl Res Cent* 2019;43:195. <https://doi.org/10.1186/s42269-019-0239-y>.
89. Shams A. Combat degradation in rain fed areas by introducing new drought tolerant crops in Egypt. *Int J Water Resour Arid Environ* 2011;1:318–25.
90. Hawu O, Ravhuhali KE, Mokoboki HK, et al. Sustainable Use of Legume Residues: Effect on Nutritive Value and Ensiling Characteristics of Maize Straw Silage. *Sustainability* 2022, Vol 14, Page 6743 2022;14:6743. <https://doi.org/10.3390/SU14116743>.
91. Chequer JAR, Carlos MAL, Flores CFA, et al. Effects of cactus (*Opuntia ficus-indica*) mucilage on boar sperm cryosurvival. *Anim Reprod* 2025;22:e20240004. <https://doi.org/10.1590/1984-3143-AR2024-0004>.
92. Moshidi PM, Sindane AS, Washaya S, et al. The effects of supplementing prickly pear (*Opuntia ficus-indica*) powder on dairy calves' health and growth performance. *S Afr J Anim Sci* 2025;55:225–36. <https://doi.org/10.4314/sajas.v55i5.01>.
93. Beretta V, Simeone A, Franco J, et al. Using sorghum dry distillers' grains plus solubles in sorghum-based finishing diets: feed utilization, cattle performance and carcass traits. *Anim Feed Sci Technol* 2021;271:114731. <https://doi.org/10.1016/j.anifeedsci.2020.114731>.
94. Wahyono T, Indiratama WM, Sihono, et al. White Midrib (WMR) vs Brown Midrib (BMR) sorghum: perspective of nutrient value for ruminant forage. *IOP Conf Ser Earth Environ Sci* 2021;788:012164. <https://doi.org/10.1088/1755-1315/788/1/012164>.
95. Ndlovu N, Usai T, Usai E, et al. Effect of dietary substitution of maize meal with finger millet meal on fat deposition on broiler meat. *Afr J Biol Sci* 2019;01:15. <https://doi.org/10.33472/AFJBS.1.4.2019.15-23>.
96. Chen X, Mi H, Cui K, et al. Effects of diets containing finger millet straw and corn straw on growth performance, plasma metabolites, immune capacity, and carcass traits in fattening Lambs. *Animals* 2020;10:1285. <https://doi.org/10.3390/ani10081285>.
97. Adeleye OO, Ogunwale OA, Olumide MD, et al. Whole pearl millet feeding does not impair performance and nutrient digestibility in 28-day-old broiler chickens. *J Anim Physiol Anim Nutr (Berl)* 2020;104:517–28. <https://doi.org/10.1111/jpn.13276>.
98. Bot MH, GS, Bawa JJ, Omege PA, et al. Growth performance of broiler chickens fed replacement levels of red and black finger millet (*Eleusine coracana*) varieties at starter phase. *Nig J Anim Sci* 2021;23:122–30.
99. Olasehinde O, Aderemi F. Effect of sprouted whole pearl millet on growth performance, intestinal development, bacterial count, and blood indices of broiler chickens. *Transl Anim Sci* 2023;7. <https://doi.org/10.1093/tas/txad045>.
100. Singh H, Malik DS, Kaur D, et al. Influence of pearl-millet-based extruded feed on the growth performance and carcass characteristics of broiler. *Ind J Poult Sci* 2023;58:87–8. <https://doi.org/10.5958/0974-8180.2023.00002.8>.
101. Zheng Y, Zhao Y, Xue S, et al. Feeding value assessment of substituting cassava (*Manihot esculenta*) residue for concentrate of dairy cows using an in vitro gas test. *Animals* 2021, Vol 11, Page 307 2021;11:307. <https://doi.org/10.3390/ANI11020307>.
102. Williams GA, Akinola OS, Adeleye TM, et al. Processed cassava peel-leaf blends: effect on performance, carcass yield, organ weights and ileal microflora of growing pigs. *Anim Prod Sci* 2023;63:751–60. <https://doi.org/10.1071/AN22101>.
103. Ojediran TK, Afolabi TS, Olayiwola SF, et al. High-quality-cassava peel meal: Impact on growth performance, blood characteristics, and economic indices of grower pigs. *Thai J Agric Sci* 2024;57:58–71.

104. Pongsub S, Suriyapha C, Boontiam W, et al. Growth performance and ruminal fermentation characteristics of Thai-native beef cattle fed cassava pulp fermented with *Lactobacillus casei* TH14 and additives. *Trop Anim Health Prod* 2024;56:356. <https://doi.org/10.1007/s11250-024-04200-x>.
105. Kandee T, Chanthakhoun V, Polyorach S. Effects of cassava leaves silage as a protein source in dietary on growth and reproductive performance of Lao native pig gilts. *IJAST* 2024;20:1075–82.
106. Subramanian A, Ramakrishnaiah A, Reddy M, et al. Effect of feeding spineless cactus (*Opuntia ficus indica*) on intake, digestibility and growth performance in lambs. *Int J Livest Res* 2017;1. <https://doi.org/10.5455/ijlr.20170613071045>.
107. Alhanafi F, Kaysi Y, Muna M, et al. Spineless cactus (*Opuntia ficus-indica*) and saltbush (*Atriplex halimus* L.) as feed supplements for fattening Awassi male lambs: effect on digestibility, water consumption, blood metabolites, and growth performance. *Trop Anim Health Prod* 2019;51:1637–44. <https://doi.org/10.1007/s11250-019-01858-6>.
108. Moula N, Humbel M, Leterrier M, et al. Effects of *Opuntia ficus-indica* on growth performance and serum parameters of broiler chicken in Algeria. *Tropicicultura* 2019;37. <https://doi.org/10.25518/2295-8010.263>.
109. Ordaz G, Juárez A, López M, et al. *Opuntia ficus-indica* as a supplement for gilts in late gestation and lactation: effects on biochemical parameters and voluntary feed intake. *J Appl Anim Res* 2021;49:404–12. <https://doi.org/10.1080/09712119.2021.1995391>.
110. Nyambali A, Mndela M, Tjelele T, et al. Growth performance, carcass characteristics and economic viability of nguni cattle fed diets containing graded levels of *Opuntia ficus-indica*. *Agriculture* 2022;12:1023. <https://doi.org/10.3390/agriculture12071023>.
111. Miron J, Zuckerman E, Sadeh D, et al. Yield, composition and in vitro digestibility of new forage sorghum varieties and their ensilage characteristics. *Anim Feed Sci Technol* 2005;120:17–32. <https://doi.org/10.1016/j.anifeedsci.2005.01.008>.
112. Rana AS, Ahmad A-H, Saleem N, et al. Differential response of sorghum cultivar for fodder yield and quality. *J Glob Innov Agric Sci* 2014;2:6–10. <https://doi.org/10.17957/JGIASS/2.1.437>.
113. Bean BW, Baumhardt RL, McCollum FT, et al. Comparison of sorghum classes for grain and forage yield and forage nutritive value. *Field Crops Res* 2013;142:20–6. <https://doi.org/10.1016/j.fcr.2012.11.014>.
114. Pinho RMA, Santos EM, Oliveira JS de, et al. Sorghum cultivars of different purposes silage. *Ciência Rural* 2015;45:298–303. <https://doi.org/10.1590/0103-8478cr20131532>.
115. Behling Neto A, Reis RHP dos, Cabral L da S, et al. Nutritional value of sorghum silage of different purposes. *Ciência e Agrotecnologia* 2017;41:288–99. <https://doi.org/10.1590/1413-70542017413038516>.
116. Sajimin S, Purwantari ND, . S, et al. Evaluation on performance of some Sorghum bicolor cultivars as forage resources in the dry land with dry climate. *Jurnal Ilmu Ternak Dan Veteriner* 2018;22:135. <https://doi.org/10.14334/jitv.v22i3.1611>.
117. Kapustin S, Volodin A, Kapustin A, et al. Feed quality of new sudan grass varieties. *J Agric Nat* 2022;25:400–5. <https://doi.org/10.18016/KSUTARIMDOGA.VI.916295>.
118. Silva RC, Ferreira MA, Oliveira JCV, et al. Orelha de Elefante Mexicana *Opuntia stricta* ([Haw.] Haw.) spineless cactus as an option in crossbred dairy cattle diet. *S Afr J Anim Sci* 2018;48:516. <https://doi.org/10.4314/sajas.v48i3.12>.
119. Pessoa DV, Pereira de Andrade A, Rodrigues Magalhães AL, et al. Forage nutritional differences within the genus *Opuntia*. *J Arid Environ* 2020;181:104243. <https://doi.org/10.1016/j.jaridenv.2020.104243>.
120. Ramos JP de F, Macêdo AJ da S, Santos EM, et al. Forage yield and morphological traits of cactus pear genotypes. *Acta Sci Agron* 2021;43:e51214. <https://doi.org/10.4025/actasciagron.v43i1.51214>.
121. Teklu GW, Ayimut K-M, Abera FA, et al. Nutritive and chemical composition and in vitro digestibility of cladodes of the *Opuntia* Species. *Sustainability* 2023;15:6624. <https://doi.org/10.3390/su15086624>.
122. National Research Council, Committee on Animal Nutrition, Subcommittee on Dairy Cattle Nutrition. *Nutrient Requirements of Dairy Cattle: Seventh Revised Edition, 2001*. National Academies Press 2001.
123. Alves FAL, dos Santos DC. Morphological and nutritional characterization of the cladodes of seven varieties of forage cactus of the genus *Opuntia* cultivated in Brazil. *S Afri J Bot* 2024;169:46–55. <https://doi.org/10.1016/j.sajb.2024.04.020>.

124. Manopriya S, Aberathna AAAU, Satharasinghe DA, et al. Importance of Phosphorus in Farm Animals. *Iran J Appl Anim Sci* 2022;12:203–10.
125. Dambreville A, Lauri P-É, Normand F, et al. Analysing growth and development of plants jointly using developmental growth stages. *Ann Bot* 2015;115:93–105. <https://doi.org/10.1093/aob/mcu227>.
126. Mahmood T, Anwar F, Abbas M, et al. Compositional Variation in Sugars and Organic Acids at Different Maturity Stages in Selected Small Fruits from Pakistan. *Int J Mol Sci* 2012;13:1380–92. <https://doi.org/10.3390/ijms13021380>.
127. Atis I, Konuskan O, Duru M, et al. Effect of harvesting time on yield, composition and forage quality of some forage sorghum cultivars. *Int J Agric Biol* 2012;14:879–86.
128. Júnior FWG, Gonçalves LC, Júnior RWT V, et al. Effect of grain maturity stage on the quality of sorghum BRS-610 silages. *Arq Bras Med Vet Zootec* 2011;12:15–23.
129. Mwangi P. Effect of stage of growth on nutritional value of dual purpose sorghum [PhD dissertation]. University of Nairobi, 2016.
130. Terler G, Resch R, Gappmaier S, et al. Nutritive value for ruminants of different fresh and ensiled sorghum (*Sorghum bicolor* (L.) Moench) varieties harvested at varying maturity stages. *Arch Anim Nutr* 2021;75:167–82. <https://doi.org/10.1080/1745039X.2021.1924016>.
131. da Silva CS, TMaia FJ, Lourenço JM, et al. The impact of maturity stages on yield, quality, and nutritive value of ensiled Johnsongrass [*Sorghum halepense* (L.) Pers]. *Transl Anim Sci* 2022;6. <https://doi.org/10.1093/tas/txac118>.
132. Alatürk F. Effects of harvest height and time on hay yield and quality of some sweet sorghum and sorghum Sudangrass hybrid varieties. *PeerJ* 2024;12:e17274. <https://doi.org/10.7717/peerj.17274>.
133. Hakim A, Fazriyah NR, Rayani TF, et al. The effect of different harvest ages on the productivity of maize and sorghum green fodder. *E3S Web of Conferences* 2024;577:02009. <https://doi.org/10.1051/e3sconf/202457702009>.
134. Moura MMA, Roseira JPS, Alves WS, et al. Effect of maturity stage on sorghum silage production: intake, digestibility, energy partition, and methane production in sheep 2024. <https://doi.org/10.21203/rs.3.rs-4523679/v1>.
135. Juhaimi F Al, Ghafoor K, Uslu N, et al. The effect of harvest times on bioactive properties and fatty acid compositions of prickly pear (*Opuntia ficus-barbarica* A. Berger) fruits. *Food Chem* 2020;303:125387. <https://doi.org/10.1016/j.foodchem.2019.125387>.
136. Da Silva DD, De Andrade AP, Da Silva DS, et al. Nutritional quality of *Opuntia* spp. at different phenological stages: Implications for forage purposes. *J Agric Stud* 2021;10:48. <https://doi.org/10.5296/jas.v10i1.19199>.
137. Maiuolo J, Nucera S, Serra M, et al. Cladodes of *Opuntia ficus-indica* (L.) Mill. Possess Important Beneficial Properties Dependent on Their Different Stages of Maturity. *Plants* 2024;13:1365. <https://doi.org/10.3390/plants13101365>.
138. Fulgueira CL, Amigot SL, Gaggiotti ML, et al. Forage quality: Techniques for testing. *Fresh Prod* 2007;1:121–31.
139. Ahmad MShamsher, SMWasim, AMS and SMWasim. Factors affecting postharvest quality of fresh fruits. *Postharvest Quality Assurance of Fruits: Practical Approaches for Developing Countries* 2015:7–32.
140. Salem AZM, Hassan AA, Khalil MS, et al. Effects of sun-drying and exogenous enzymes on nutrients intake, digestibility and nitrogen utilization in sheep fed *Atriplex halimus* foliages. *Anim Feed Sci Technol* 2012;171:128–35. <https://doi.org/10.1016/J.ANIFEEDSCI.2011.10.011>.
141. Ramsumair A, Mlambo V, Lallo CHO. Effect of drying method on the chemical composition of leaves from four tropical tree species. *Trop Agric* 2014;91:179–86.
142. Lahiru PB, Jayaweera BPA. Alternative roughage feed Production under different drying methods and evaluation of the feeding value. *Wayamba J Anim Sci* 2017;9:1405.
143. Suwignyo B, Mustika A, Kustantinah, et al. Effect of drying method on physical-chemical characteristics and amino acid content of tropical alfalfa (*Medicago sativa* L.) hay for poultry feed. *Am J Anim Vet Sci* 2020;15. <https://doi.org/10.3844/ajavsp.2020.118.122>.

144. Soto GM, Fabián FC, Pérez TH, et al. Effect of Drying Methods on the Nutraceutical Potential of Cactus Cladodes (*Opuntia* spp.). *Int J Food Sci Nutr* 2016;2:1–6. <https://doi.org/10.15436/2377-0619.15.023>.
145. Ferreira RM, Wessel DF, Silva AMS, et al. Infusion from *Opuntia ficus-indica* peels: The effects of drying and steeping conditions. *Beverages* 2023;9:97. <https://doi.org/10.3390/beverages9040097>.
146. Abidi S, Ben Salem H, Vasta V, et al. Supplementation with barley or spineless cactus (*Opuntia ficus indica* f. *inermis*) cladodes on digestion, growth and intramuscular fatty acid composition in sheep and goats receiving oaten hay. *Small Rum Res* 2009;87:9–16. <https://doi.org/10.1016/j.smallrumres.2009.09.004>.
147. Aruwa CE, Amoo S, Kudanga T. Phenolic compound profile and biological activities of Southern African *Opuntia ficus-indica* fruit pulp and peels. *LWT- Food Sci and Tech* 2019;111:337–44. <https://doi.org/10.1016/j.lwt.2019.05.028>.
148. Gouws CA, D’Cunha NM, Georgousopoulou EN, et al. The effect of different drying techniques on phytochemical content and in vitro antioxidant properties of Australian-grown prickly pears (*Opuntia ficus indica*). *J Food Process Preserv* 2019;43:e13900. <https://doi.org/10.1111/jfpp.13900>.
149. El Hajji L, Azzouzi H, Achchoub M, et al. Nutritional improvement of cactus fruit scraps with addition of alfalfa or *Atriplex halimus*, and comparison of two animal feed preservation methods (silage and solar drying). *Afr J Range Forage Sci* 2024;41:196–203. <https://doi.org/10.2989/10220119.2024.2341726>.
150. Maniaci G, Ponte M, Giosuè C, et al. Cladodes of *Opuntia ficus-indica* (L.) as a source of bioactive compounds in dairy products. *J Dairy Sci* 2024;107:1887–902. <https://doi.org/10.3168/jds.2023-23847>.
151. Zhang Y, Chen F, Zhang Y, et al. Experimental investigations of interactions between a laser-induced cavitation bubble and a spherical particle. *Exp Therm Fluid Sci* 2018;98:645–61. <https://doi.org/10.1016/j.expthermflusci.2018.06.014>.
152. Iskenderov R, Lebedev A, Zacharin A, et al. Evaluating effectiveness of grinding process grain materials. *Eng Rural Dev* 2018;17:102–8. <https://doi.org/10.22616/ERDev2018.17.N147>.
153. Kiarie EG, Mills A. Role of feed processing on gut Health and function in pigs and poultry: Conundrum of optimal particle size and hydrothermal regimens. *Front Vet Sci* 2019;6. <https://doi.org/10.3389/fvets.2019.00019>.
154. Liermann W, Bochnia M, Berk A, et al. Effects of Feed Particle Size and Hydro-Thermal Processing Methods on Starch Modification, Nutrient Digestibility and the Performance and the Gastrointestinal Tract of Broilers. *Animals* 2019;9:294. <https://doi.org/10.3390/ani9060294>.
155. Chen T, Chen D, Tian G, et al. Effects of soluble and insoluble dietary fiber supplementation on growth performance, nutrient digestibility, intestinal microbe and barrier function in weaning piglet. *Anim Feed Sci Technol* 2020;260:114335. <https://doi.org/10.1016/j.anifeedsci.2019.114335>.
156. Lyu F, Thomas M, van der Poel AFB, et al. The importance of particle size on organic matter and crude protein in vitro digestibility of maize and soybean meal. *Anim Feed Sci Technol* 2022;285:115243. <https://doi.org/10.1016/j.anifeedsci.2022.115243>.
157. Iskakov R, Gulyarenko A, Hyla P, et al. Working parts for intensive crushing and grinding of feed from waste raw materials: A review. *Advances in Science and Technology Research Journal* 2025;19:98–131. <https://doi.org/10.12913/22998624/203643>.
158. Al-Rabadi GJ, Hosking BJ, Torley PJ, et al. Regrinding large particles from milled grains improves growth performance of pigs. *Anim Feed Sci Technol* 2017;233:53–63. <https://doi.org/10.1016/J.ANIFEEDSCI.2016.08.004>.
159. Savinyh P, Shirobokov V, Fedorov O, et al. Influence of rotary grain crusher parameters on quality of finished product. *Eng Rural Dev* 2018;17:131–6. <https://doi.org/10.22616/ERDev2018.17.N158>.
160. Iskakov R, Gulyarenko A, Bembenek M, et al. Technologies for efficient grinding of plant and animal waste: a review. *EUREKA: Physics and Engineering* 2025:54–77. <https://doi.org/10.21303/2461-4262.2025.003733>.
161. Romero C, Nicodemus N, Carabaño R, et al. Evaluation of type of grinding of lucerne hay and wheat straw in diets for growing rabbits with two levels of neutral detergent fibre. *Anim Feed Sci Technol* 2025;319:116193. <https://doi.org/10.1016/J.ANIFEEDSCI.2024.116193>.
162. Ray RC, Bari LM, Isobe S. Agro-industrial bioprocessing of tropical root and tuber crops—Current research and future prospects. *Ind Exp Microorg* 2010:352–74.

163. Ramos JPF, Santos EM, Santos APM, et al. Ensiling of forage crops in semiarid regions. In: Da Silva T, Santos EM, editors. *Advances in Silage Production and Utilization*, Rijeka: InTech; 2016, p. 67–83.
164. Ávila CLS, Carvalho BF. Silage fermentation—updates focusing on the performance of micro-organisms. *J Appl Microbiol* 2020;128:966–84. <https://doi.org/10.1111/jam.14450>.
165. Naeini ShahabodinZ, Emami NimaK, Rowghani E, et al. Influence of ensiling time on chemical composition, fermentation characteristics, gas production and protein fractions of sweet sorghum silage. *Res Opin Anim Vet Sci* 2014;4:286–93.
166. Bao J, Wang L, Yu Z. Effects of Different Moisture Levels and Additives on the Ensiling Characteristics and In Vitro Digestibility of Stylosanthes Silage. *Animals* 2022;12:1555. <https://doi.org/10.3390/ANI12121555>.
167. Lin J, Li G, Sun L, et al. Varieties and ensiling: Impact on chemical composition, fermentation quality and bacterial community of alfalfa. *Front Microbiol* 2023;13:1091491. <https://doi.org/10.3389/FMICB.2022.1091491/BIBTEX>.
168. Forwood DL, Hooker K, Caro E, et al. Crop sorghum ensiled with unsalable vegetables increases silage microbial diversity. *Front Microbiol* 2019;10. <https://doi.org/10.3389/fmicb.2019.02599>.
169. Ziv C, Fallik E. Postharvest storage techniques and quality evaluation of fruits and vegetables for reducing food loss. *Agronomy* 2021;11:1133. <https://doi.org/10.3390/agronomy11061133>.
170. Valenzuela JL. Advances in postharvest preservation and quality of fruits and vegetables. *Foods* 2023;12:1830. <https://doi.org/10.3390/foods12091830>.
171. Wallace PA, Adu EK, Rhule SWA. Optimal storage conditions for cocoa cake with shell, palm kernel cake and copra cake as poultry and livestock feed in Ghana 2010. <http://lrrd.cipav.org.co/lrrd22/2/wall22032.htm> (accessed June 18, 2025).
172. Wang B, Luo Y, Myung KH, et al. Effects of storage duration and temperature on the chemical composition, microorganism density, and rumen fermentation of wet brewers grains. *Asian-Australas J Anim Sci* 2014;27:832–40. <https://doi.org/10.5713/ajas.2013.13668>.
173. Lozano-Ojalvo D, Rodríguez A, Bernáldez V, et al. Influence of temperature and substrate conditions on the omt-1 gene expression of *Aspergillus parasiticus* in relation to its aflatoxin production. *Int J Food Microbiol* 2013;166:263–9. <https://doi.org/10.1016/j.ijfoodmicro.2013.07.011>.
174. Mannaa M, Kim KD. Influence of temperature and water activity on deleterious fungi and mycotoxin production during grain storage. *Mycobiology* 2017;45:240–54. <https://doi.org/10.5941/MYCO.2017.45.4.240>.
175. Rathod A, Kumawat M. Storage of feed ingredients and finished feed. *Indian Farmer* 2024;11:77–82.
176. Negash D. A review of aflatoxin: Occurrence, prevention, and gaps in both food and feed safety. *J Appl Microbiol Res* 2018;1:34–43.
177. Kirigia D, Winkelmann T, Kasili R, et al. Development stage, storage temperature and storage duration influence phytonutrient content in cowpea (*Vigna unguiculata* L. Walp.). *Heliyon* 2018;4:e00656. <https://doi.org/10.1016/j.heliyon.2018>.
178. Bragança GCM, Ziegler V, Ávila BP, et al. Multivariate analysis of the conditions of temperature, moisture and storage time in the technological, chemical, nutritional parameters and phytochemical of green lentils. *J Stored Prod Res* 2020;87:101617. <https://doi.org/10.1016/J.JSPR.2020.101617>.
179. Swart WJ, Swart VR. An overview of research on diseases of cactus pear in South Africa. *J Prof Assoc Cactus Dev* 2003;5:115–20.
180. Flores RF, del Valle MGV, Rodríguez RL, et al. Identification of fungal species associated with cladode spot of prickly pear and their sensitivity to chitosan. *Journal of Phytopathol* 2013;161:544–52. <https://doi.org/10.1111/jph.12104>.
181. Cervera CZL, Salinas QA, Ramírez VP, et al. Fungal causal agents of the Black Spot of the cactus (*Opuntia ficus-indica*) in Colima, Mexico. *Mex J Phytopathol* 2024;42. <https://doi.org/https://doi.org/10.18781/r.mex.fit.2401-2>.
182. Wegulo S, Giesler L, Harveson R, et al. Impacts of drought on disease development and management. *Papers Plant Pathol* 2013. <http://digitalcommons.unl.edu/plantpathpapers> (accessed December 10, 2025).

183. Hamidou F, Rathore A, Waliyar F, et al. Although drought intensity increases aflatoxin contamination, drought tolerance does not lead to less aflatoxin contamination. *Field Crops Res* 2014;156:103–10. <https://doi.org/10.1016/j.fcr.2013.10.019>.
184. Ssepuuya G, Van Poucke C, Ediage EN, et al. Mycotoxin contamination of sorghum and its contribution to human dietary exposure in four sub-Saharan countries. *Food Addit Contam, Part A* 2018;35:1384–93. <https://doi.org/10.1080/19440049.2018.1461253>.
185. Nkomo G V., Sedibe MM, Mofokeng MA. Production Constraints and Improvement Strategies of Cowpea (*Vigna unguiculata* L. Walp.) Genotypes for Drought Tolerance. *Int J Agron* 2021;2021:1–9. <https://doi.org/10.1155/2021/5536417>.
186. Queiroz OCM, Ogunade IM, Weinberg Z, et al. Silage review: Foodborne pathogens in silage and their mitigation by silage additives. *J Dairy Sci* 2018;101:4132–42. <https://doi.org/10.3168/jds.2017-13901>.
187. FAO, IFIF. Good practices for the feed industry – Implementing the Codex Alimentarius code of practice on good animal feeding. FAO animal production and health manual No. 9. Rome: 2010.
188. Tufarelli V, Puvača N, Glamović D, et al. The most important metabolic diseases in dairy cattle during the transition period. *Animals* 2024;14:816. <https://doi.org/10.3390/ani14050816>.
189. National Academies of Sciences E and M, Division on Earth and Life Studies, Committee on Nutrient Requirements of Beef Cattle. Nutrient Requirements of beef cattle: eighth revised edition. National Academies Press; 2021. <https://doi.org/10.17226/19014>.
190. Rashwan AK, Osman AI, Abdelshafy AM, et al. Plant-based proteins: advanced extraction technologies, interactions, physicochemical and functional properties, food and related applications, and health benefits. *Crit Rev Food Sci Nutr* 2025;65:667–94. <https://doi.org/10.1080/10408398.2023.2279696>.
191. Brink M, Janssens GPJ, Demeyer P, et al. Reduction of dietary crude protein and feed form: Impact on broiler litter quality, ammonia concentrations, excreta composition, performance, welfare, and meat quality. *Anim Nutr* 2022;9:291–303. <https://doi.org/10.1016/j.aninu.2021.12.009>.
192. Kurniawan A, Natsir MH, Suyadi S, et al. The effect of feeding with different protein levels on internal organ weight and gene expression of MEF2A and ATF3 in crossbred local chicken using RT-PCR. *J Genet Eng Biotechnol* 2023;21:83. <https://doi.org/10.1186/s43141-023-00533-6>.
193. Zhu W, Xu W, Wei C, et al. Effects of Decreasing Dietary Crude Protein Level on Growth Performance, Nutrient Digestion, Serum Metabolites, and Nitrogen Utilization in Growing Goat Kids (*Capra hircus*). *Animals* 2020, Vol 10, Page 151 2020;10:151. <https://doi.org/10.3390/ANI10010151>.
194. Lalman D, Holder A. Nutrient requirements of beef cattle. Oklahoma: 2023.
195. Almaz A, Tamir B, Melaku S. Feed Intake, digestibility and live weight change of lambs fed finger millet (*Eleusine coracana*) straw supplemented with atella, noug Seed (*Guizotia abyssinica*) cake and their mixtures. *Agric Trop Subtrop* 2012;45. <https://doi.org/10.2478/v10295-012-0018-3>.
196. Agustin F, Erpomen, Ningrat RWS. The Use of Cassava Peel as a Source of Energy for Substituting Rice Bran in Ration Containing *Gliricidia maculata* Leaves in Dairy Cows. *IOP Conf Ser Earth Environ Sci* 2020;478:012077. <https://doi.org/10.1088/1755-1315/478/1/012077>.
197. Gannuscio R, Vastolo A, Maniaci G, et al. Improve nutritive value of silage based on prickly pear peel by-products. *Ital J Anim Sci* 2024;23:492–503. <https://doi.org/10.1080/1828051X.2024.2323629>.
198. Lavery A, Craig A, Gordon AW, et al. Reducing dietary crude protein levels while meeting metabolizable protein requirements: Performance of dairy cows over a full lactation period. *J Dairy Sci* 2025;108:1451–73. <https://doi.org/10.3168/jds.2024-25405>.
199. Brainer MM de A, Rabello CB-V, Batista dos Santos MJ, et al. Crude protein requirements of free-range laying hens. *Anim Prod Sci* 2016;56:1622. <https://doi.org/10.1071/AN14890>.
200. Jia Z, Zhou J, Yang M, et al. Preparation and evaluation of certified reference materials for crude protein, crude fat, and crude ash in feed. *Microchem J* 2023;191:108854. <https://doi.org/10.1016/j.microc.2023.108854>.
201. Singh S, Bhat BV, Shukla GP, et al. Nutritional evaluation of different varieties of sorghum stovers in sheep. *Anim Feed Sci Technol* 2017;227:42–51. <https://doi.org/10.1016/j.anifeeds.2017.03.011>.
202. Santhosh AV, Ramachandra B, Manjunatha H, et al. Exploring nutritional diversity in millets: A comparative study on protein and crude fiber content. *J Sci Res Rep* 2024;30:458–65. <https://doi.org/10.9734/jsrr/2024/v30i112573>.

203. Murugan S, Paramasivam SK, Nedunchezhiyan M, et al. Sweet potato as animal feed and fodder. *Fruit Veg Cereal Sci Biotech* 2012;6:106–4.
204. Rodrigues AM, Pitacas FI, Reis CMG, et al. Nutritional value of *Opuntia ficus-indica* cladodes from Portuguese ecotypes. *Bulg J Agric Sci* 2016;22:40–5.
205. Dias CSAMM, Nunes HPB, Vouzela CFM, et al. Influence of the season on the nutritive value and gas production of *Opuntia ficus-indica* and *Agave americana* L. in ruminant feed. *Animals* 2023;13:1008. <https://doi.org/10.3390/ani13061008>.
206. Oladimeji SO, Adeyemi AA, Mosuro AO, et al. Nutritional composition of cassava (*Manihot esculenta* Crantz) peel products. *Livest Res Rural Dev* 2022;34:1–7.
207. Liu C, Asano S, Ogata H, et al. Digestive, fermentative, and physical properties of pineapple residue as a feed for cattle. *Anim Sci J* 2021;92. <https://doi.org/10.1111/asj.13535>.
208. Kyawt Y, Win K, Mu K, et al. Feeding pineapple waste silage as roughage source improved the nutrient intakes, energy status and growth performances of growing Myanmar local cattle. *J Adv Vet Anim Res* 2020;7:436. <https://doi.org/10.5455/javar.2020.g439>.
209. Frei M. Lignin: Characterization of a multifaceted crop Component. *Sci World J* 2013;1:436517. <https://doi.org/10.1155/2013/436517>.
210. Getachew G, Laca EA, Putnam DH, et al. The impact of lignin downregulation on alfalfa yield, chemical composition, and in vitro gas production. *J Sci Food Agric* 2018;98:4205–15. <https://doi.org/10.1002/jsfa.8942>.
211. Casler MD. Breeding forage crops for increased nutritional value. *Adv in Agron* 2001;71:51–107. [https://doi.org/10.1016/S0065-2113\(01\)71012-7](https://doi.org/10.1016/S0065-2113(01)71012-7).
212. Cannas A, Van Soest PJ, Pell AN. Use of animal and dietary information to predict rumen turnover. *Anim Feed Sci Technol* 2003;106:95–117. [https://doi.org/10.1016/S0377-8401\(02\)00255-9](https://doi.org/10.1016/S0377-8401(02)00255-9).
213. Riboulet C, Lefèvre B, Dénoue D, et al. Genetic variation in maize cell wall for lignin content, lignin structure, p-hydroxycinnamic acid content, and digestibility in set of 19 lines at silage harvest maturity. *Maydica* 2008;53:11.
214. Stypinski JD, Weiss WP, Carroll AL, et al. Effect of acid detergent lignin concentration for diets formulated to be similar in neutral detergent fiber content on energy utilization in lactating Jersey cows. *J Dairy Sci* 2024;107:5699–708. <https://doi.org/10.3168/jds.2023-24318>.
215. Zhong H, Zhou J, Abdelrahman M, et al. The Effect of Lignin Composition on Ruminal Fiber Fractions Degradation from Different Roughage Sources in Water Buffalo (*Bubalus bubalis*). *Agriculture* 2021;11:1015. <https://doi.org/10.3390/agriculture11101015>.
216. Zhong H, Zhou J, Abdelrahman M, et al. The effect of lignin composition on ruminal fiber fractions degradation from different roughage sources in water buffalo (*Bubalus bubalis*). *Agriculture* 2021;11:1015. <https://doi.org/10.3390/agriculture11101015>.
217. Atuhaire AM, Kabi F, Okello S, et al. Optimizing bio-physical conditions and pre-treatment options for breaking lignin barrier of maize stover feed using white rot fungi. *Animal Nutrition* 2016;2:361–9. <https://doi.org/10.1016/J.ANINU.2016.08.009>.
218. Huang H, Wang Z, Pan SC, et al. Fungal pretreatment to improve digestibility of corn stover for animal feed. *Trans ASABE* 2017;60:973–9. <https://doi.org/10.13031/TRANS.12042>.
219. Jędrzejczyk M, Soszka E, Czapnik M, et al. Physical and chemical pretreatment of lignocellulosic biomass. In *Second and Third Generation of Feedstocks*, Elsevier; 2019, p. 143–96. <https://doi.org/10.1016/B978-0-12-815162-4.00006-9>.
220. Agbor VB, Cicek N, Sparling R, et al. Biomass pretreatment: Fundamentals toward application. *Biotechnol Adv* 2011;29:675–85. <https://doi.org/10.1016/j.biotechadv.2011.05.005>.
221. Escapa A, Gil-Carrera L, García V, et al. Performance of a continuous flow microbial electrolysis cell (MEC) fed with domestic wastewater. *Bioresour Technol* 2012;117:55–62. <https://doi.org/10.1016/j.biortech.2012.04.060>.
222. Kusmiati R, Syaputri Y, Abun, et al. Pretreatment and fermentation of lignocellulose from oil palm fronds as a potential source of fibre for ruminant feed: a review. *J Sustain Agric Environ* 2024;3. <https://doi.org/10.1002/sae2.70003>.

223. Lee H. The Current Status and Constraints of Drought-Tolerant Maize Adoption in Uganda. *Open Agric J* 2020;14:98–107. <https://doi.org/10.2174/1874331502014010098>.
224. Rao AS. Climate and microclimate changes influencing the fauna of the hot Indian arid zone. In *Faunal Ecology and Conservation of the Great Indian Desert*, Berlin, Heidelberg: Springer; 2009, p. 13–23. https://doi.org/10.1007/978-3-540-87409-6_2.
225. E Silva MF, Van Schoubroeck S, Cools J, et al. A systematic review identifying the drivers and barriers to the adoption of climate-smart agriculture by smallholder farmers in Africa. *Front Environ Econ* 2024;3:1356335. <https://doi.org/10.3389/FREVC.2024.1356335/BIBTEX>.
226. Kamara AY, Adesiyani AT, Oyinbo O, et al. Improving the productivity and income of smallholder sorghum farmers: The role of improved crop varieties in Nigeria. *Food and Energy Secur* 2025:e70058. <https://doi.org/10.1002/fes3.70058>.
227. Westengen OT, Dalle SP, Mulesa TH. Navigating toward resilient and inclusive seed systems. *Proc Natl Acad Sci* 2023;120. <https://doi.org/10.1073/pnas.2218777120>.
228. Acevedo M, Pixley K, Zinyengere N, et al. A scoping review of adoption of climate-resilient crops by small-scale producers in low- and middle-income countries. *Nat Plants* 2020;6:1231–41. <https://doi.org/10.1038/S41477-020-00783-Z;SUBJMETA>.
229. Du Preez CC, Van Huyssteen CW, Mnkeni PNS. Land use and soil organic matter in South Africa 1: A review on spatial variability and the influence of rangeland stock production. *S Afr J Sci* 2011;107. <https://doi.org/10.4102/SAJS.V107I5/6.354>.
230. Olabanji MF, Chitakira M. The adoption and scaling of climate-smart agriculture innovation by smallholder farmers in South Africa: A review of institutional mechanisms, policy frameworks and market dynamics. *World* 2025;6:51. <https://doi.org/10.3390/world6020051>.
231. Zougmoré R, Partey S, Ouédraogo M, et al. Toward climate-smart agriculture in West Africa: a review of climate change impacts, adaptation strategies and policy developments for the livestock, fishery and crop production sectors. *Agric Food Secur* 2016;5:26. <https://doi.org/10.1186/s40066-016-0075-3>.
232. Lunduka RW, Mateva KI, Magorokosho C, et al. Impact of adoption of drought-tolerant maize varieties on total maize production in south Eastern Zimbabwe. *Clim Dev* 2019;11:35–46. <https://doi.org/10.1080/17565529.2017.1372269;WGROU:STRING:PUBLICATION>.
233. Omotoso AB, Omotayo AO. Impact of behavioural intention to adopt climate-smart agricultural practices on the food and nutrition security of farming households: Microeconomic level evidence. *Clim Change* 2024;177:1–25. <https://doi.org/10.1007/S10584-024-03775-6>.
234. Wongnaa CA, Seyram AA, Babu S. A systematic review of climate change impacts, adaptation strategies, and policy development in West Africa. *Reg Sustain* 2024;5:100137. <https://doi.org/10.1016/j.regsus.2024.100137>.
235. Vollum SDK, Raha D, Koomson D. Climate change impact and adaptation: Lagoonal fishing communities in West Africa 108. In *African handbook of climate change adaptation*, 2021. https://doi.org/10.1007/978-3-030-45106-6_221.
236. Sorgho R, Quiñonez CAM, Louis VR, et al. Climate change policies in 16 West African countries: A systematic review of adaptation with a focus on agriculture, food security, and nutrition. *Int J Environ Res Public Health* 2020;17:8897. <https://doi.org/10.3390/ijerph17238897>.
237. Capstaff NM, Miller AJ. Improving the Yield and Nutritional Quality of Forage Crops. *Front Plant Sci* 2018;9:535. <https://doi.org/10.3389/FPLS.2018.00535>.
238. Palmer N, Neno S, Smith G, et al. CIAT Annual report 2015-2016 A synthesis: Sustainable food futures getting the fundamentals right. Cali, Colombia: International Center for Tropical Agriculture; 2016.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.