Improving Nutritional Management and Forage Recommendations for Ruminant Producers in Tennessee

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ABSTRACT

Forage management and utilization are important components of sustainable livestock production systems. In Tennessee and throughout the southeastern United States, producers face challenges associated with seasonal forage availability, forage quality, nutrient management, and access to relevant educational resources. Therefore, the objectives of this thesis were to evaluate the effects of forage nitrate concentration and dried distillers' grains (DDG) inclusion on in vitro true digestibility (IVTD) and to identify forage-related educational priorities among Tennessee small ruminant producers.

The digestibility study evaluated sorghum-sudangrass (*Sorghum bicolor* var. *bicolor* × *bicolor* var. *sudanense*), a warm-season annual forage susceptible to nitrate accumulation under environmental stress and elevated nitrogen fertilization. Sorghum-sudangrass was grown under nitrogen fertilization rates ranging from 0 to 202 kg N/ha, producing four forage categories with nitrate concentrations of 158, 517, 3,483, and 8,365 mg/kg. Forage was evaluated alone or as a 50:50 forage–DDG mixture using an ANKOM DaisyII incubator and rumen inoculum collected from a fistulated beef cow. Samples were incubated for 48 h before IVTD determination. DDG inclusion significantly affected total-substrate IVTD ($P < 0.001$), whereas no effect of forage nitrate category ($P = 0.471$) or DDG × nitrate category interaction ($P = 0.252$) was detected. These results indicate greater IVTD of the 50:50 forage–DDG mixtures than forage alone under the conditions of this in vitro system.

The needs assessment was conducted online during November 2025 and received 201 responses, of which 182 met Tennessee eligibility criteria and represented 68

counties. Respondents independently rated 11 forage-related educational topics using a five-point Likert-type scale. The highest mean ratings were extending the grazing season (4.47), hay and forage quality (4.32), forage-related health problems (4.28), and pasture assessment (4.24). Among eligible respondents, 52% were female, 27% were 45 to 54 years of age, and 30% reported 10 or more years of small ruminant production experience.

Collectively, these studies provide preliminary information on total-substrate digestibility of sorghum-sudangrass–DDG mixtures and identify forage educational priorities among participating Tennessee small ruminant producers. The findings can guide future in vivo research and inform development of targeted Extension educational resources.

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CHAPTER ONE

LITERATURE REVIEW

Introduction

Forages comprise the largest feed supply for grazing livestock producers in the Southeast United States (US), operations rely on forage-only diets. However, operations feeding grain-based diets are subject to increased feed prices and fluctuations in prices within years; nearly 40% of a cow-calf operation's total input cost is nutrition-based, with this percentage expected to continue to grow (Lalman, 2021). On average, livestock operations in Tennessee supplement conserved forages for 100 to 150 days of the year (Griffith et al., 2019). Even with the use of warm- season and cool-season forage types, a substantial loss of production occurs during the summer and winter months. Research conducted in Tennessee has demonstrated that incorporating warm-season grasses into forage-based beef systems can provide grazing opportunities during periods of reduced cool-season forage production (Boyer et al., 2020). In an attempt to bridge the summer and winter gaps, some recommended strategies such as rotational grazing, stockpiling forages, and properly managing annuals to reseed are all used to extend time spent on pasture (Furlan and Pedreira, 2025). Even with best management practices, grazing will not last year-round.

During the dormant season, specifically in cattle operations, over half of the annual cost of feeding a cow occurs during the winter months (Morgan, 2023). Many operations rely on the use of stored forages during this time. Maintaining high forage quality during the storage period can be hard in certain environmental conditions. Some livestock operations lack access to dry hay storage, such as a barn, creating significant loss's in both quality and economic value. Different storage methods consequently result

in varying losses, but storage on the ground, gravel, tires, and wooden racks are known to have the largest losses in dry matter, ranging from 30-40% (Pedreira et al., 2024). Peer-reviewed research has similarly demonstrated that storage method influences dry matter recovery, with uncovered outdoor storage generally resulting in greater losses than protected or indoor storage (Nelson et al., 1985; Scarbrough et al., 2007). Nutritive values of stored bales may also decrease, resulting from rain leaching of water-soluble nutrients and oxidation impacting protein and fibrous contents. Changes during outdoor storage may also affect forage chemical composition and digestibility, as storage conditions have been shown to influence dry matter recovery, fiber concentrations, and *in vitro* digestibility of large round hay bales (Russell et al., 1990).

Sorghum-Sudangrass

Sorghum-sudangrass (*Sorghum bicolor var. bicolor × bicolor var. sudanense),* commonly called sudex, has become a valuable forage to producers in the Southeast US. This hybrid warm-season forage is not only known for its rapid growth and high forage accumulation, growing five to ten feet tall, but also its aggressive root system that aids in allowing this forage to be more drought-resistant (SARE, 2007). Due to the rapid growing ability along with thick stems and roots, sorghum-sudangrass is also valuable in preventing weeds and erosion, which only solidifies the benefits for use in farms in the Southeast US. Sorghum-sudangrass is widely adaptable and responds well to nitrogen. By incorporating this forage into a cool-season perennial system, sorghum-sudangrass will improve total forage production and quality during the summer months.

The southeastern region of the United States has a rapidly changing climate, with extreme temperatures in the summer often accompanied by drought, large amounts of rain during certain periods of the year, while still experiencing freezing temperatures in the winter months. Some forage species often cannot withstand these intense climatic changes, but that is an advantage for sorghum-sudangrass, as it is adapted to varying conditions. However, during extreme stress, such as in drought, nitrate accumulation can occur in sorghum-sudangrass, creating a risk for nitrate poisoning in livestock. Although sudex has many positive benefits related to forage production, producer hesitation about the use of this species can be derived from the accumulation of nitrates that can occur during extreme weather conditions. Accumulation occurs when there is a high level of soil nitrogen without enough water or sunlight to continue plant cell metabolism and continue plant cell growth (Cassida, 2012). This imbalance between nitrate uptake and nitrate utilization can be further exacerbated by plant disease, prolonged cool and cloudy weather, drought, frost, and excessive nitrogen fertilization.

Nitrate Poisoning

Sorghum-sudangrass containing nitrate concentrations greater than 2,500 ppm should be managed with caution because increasing nitrate concentrations elevate the risk of nitrate poisoning in ruminants. Normally, during the digestion of sorghum-sudangrass with safe levels of nitrates, the rumen breaks down nitrates to nitrites, which then undergo degradation to produce ammonia, which in turn forms microbial proteins (Allison and Wenzel, 2019). Experimental research has demonstrated that nitrate reduction within the rumen produces nitrite as an intermediate, with subsequent reduction

contributing to ammonia production and ruminal nitrogen metabolism (Kemp et al., 1977; Wang et al., 2018). A key point in this process is to note that the reduction of nitrates to nitrites occurs more rapidly than any of the other transformations, which is why high starting levels of nitrates become a concern. After the consumption of excess levels of nitrates, nitrites are rapidly produced and then absorbed. This leads to the formation of methemoglobin, which reduces the blood's oxygen carrying capacity through the blood (Thompson, 2024). In cattle receiving high dietary nitrate, increased ruminal nitrite concentrations have been associated with increased blood methemoglobin, supporting nitrite accumulation as a primary mechanism underlying nitrate toxicity (Kemp et al., 1977). More recent research demonstrated that nitrate-derived ammonia can contribute to ruminal microbial nitrogen metabolism, although the extent of incorporation depends on the dietary and ruminal fermentation environment (Wang et al., 2018). Nitrates are expressed in parts per million, with ranges that will typically be associated with different symptoms. In Tennessee, these ranges are expressed as 0-2,500 ppm being safe with limited risk; 2,500-5,000 ppm, suggested to be fed with caution; 5,000-15,000 ppm, considered risky and to be avoided; and 15,000 ppm being toxic and not to be fed (Ball et al., 2015). Livestock can have different symptoms at varying rates of poisoning, but symptoms don't always correlate with the level of nitrates present. During mild cases, cattle will show signs of dyspnea, ataxia, weakness, tremors, cyanotic mucous membranes. In pregnant cattle, severe nitrate poisoning may result in abortion, while advanced intoxication can also cause respiratory distress, pulmonary emphysema, and rapid death.

Often, producers find cattle deceased without any prior signs. If cattle with symptoms are found early, treatment is possible. Intravenous injection of 1%-2% methylene blue can be given through a saline solution and can be completed in multiple rounds. Cattle should be removed from forage sources and handled with low stress to reduce further complications of hypoxia (Thompson, 2024).

Prevention

While sorghum-sudangrass is at risk for accumulation of nitrates, there are a variety of ways to prevent toxicity before it occurs. To prevent nitrate accumulation in forages, avoid fertilizing sudex in the summer months when drought is expected or when the soil is too dry. Nitrogen fertilization rate is an important consideration because increasing nitrogen availability can increase nitrate accumulation in sorghum-based forages, particularly when environmental conditions restrict normal plant growth and nitrate assimilation (Beyaert and Roy, 2005). To prevent the consumption of sorghum-sudangrass with potentially high nitrate levels, do not cut hay or let livestock graze during drought or extreme weather conditions (Pedreira et al., 2025).

Additionally, producers can reduce the risk of nitrate poisoning by preventing hungry animals from consuming large quantities of high-nitrate forage, including providing dry hay before turnout and limiting access to high-risk pastures. When nitrate concentrations are elevated, harvesting sorghum-sudangrass for ensiling is another management strategy because the fermentation process can reduce nitrate concentrations prior to feeding. Bai et al. (2022) reported nitrate degradation rates ranging from approximately 45 to 76% after 60 days of ensiling sorghum-sudangrass, with the extent

of nitrate degradation influenced by storage temperature and ensiling density. It is best practice to complete a soil test before planting to receive fertilizer recommendations that prevent accumulation of nitrates. Additionally, conducting a forage test around the time of harvest will provide nitrate values that can assist in feeding decisions and decrease the risk of nitrate poisoning.

Unfortunately, forage shortages during extreme summer conditions and winter dormancy are inevitable, which emphasizes the importance of proactive forage management strategies in the southeastern United States. Fortunately, there are ways to extend the grazing season by implementing strategies like rotational grazing, incorporating diverse forage species, adjusting stocking densities, and feeding confined forages. Specifically, ensiling sorghum-sudangrass provides a stable, conserved forage that can be stored for use during periods of adverse weather. During ensiling, microbial activity can contribute to nitrate degradation, although the extent of nitrate reduction depends on fermentation and storage conditions and residual nitrate may remain in the conserved forage (Bai et al., 2022).

Baleage

In the southeastern United States, frequent rainfall and high humidity often make it difficult to dry forage to the moisture content required for conventional hay production. Delayed drying increases the risk of rain damage, leaf shatter, mold development, and nutrient losses, all of which can reduce forage quality. As a result, baleage production has become an increasingly valuable forage conservation practice because forage can be harvested at a higher moisture content and preserved through anaerobic fermentation.

Harvesting forage earlier, before excessive plant maturity and prolonged field exposure, helps retain soluble carbohydrates, crude protein, and digestibility compared with conventionally dried hay. Consequently, baleage often maintains greater nutritive value and digestibility, making it an attractive and marketable forage option for livestock producers (Corriher, 2025). Baleage is different from the other types of conserved forages as it is baled with moisture ranging between 40%-60%, then wrapped in 6 layers of plastic, completely sealing the forage to create an anaerobic environment (Stewart et al.,2024). Bacteria in the wrapped bale consume any available oxygen within a few hours and begin the fermentation process. The fermentation process can be broken down into 4 stages: aerobic, anaerobic, stable, and feedout. Fermentation can take up to 6-8 weeks under ideal conditions. Lactic acid is produced from plant sugars in this process, which lowers the pH of the bale and creates a stable environment (Coblentz, 2021). Proper storage of baleage is essential to maintaining forage quality. During transportation from the wrapping location to the storage site, care must be taken to avoid puncturing or tearing the plastic wrap, as damage allows oxygen to enter the bale and disrupt anaerobic fermentation. When properly wrapped, handled, and stored, baleage can be safely preserved for at least 12 months and often longer without substantial losses in forage quality, provided the plastic remains intact (Corriher, 2025). Because baleage can preserve more of the forage's nutritive value and digestibility than conventionally dried hay, producers in the southeastern United States may consider harvesting sorghum-sudangrass as baleage. This practice allows producers to harvest forage at the optimal stage of maturity without waiting for the extended drying periods required for hay

production, thereby reducing weather-related field losses and preserving forage quality. Combining the production and quality characteristics of sorghum-sudangrass with baleage production can allow for multiple cuttings, resulting in bales with high nutritive value. Although nitrate accumulation is prevalent in sorghum-sudangrass, the ensiling process has been shown to reduce nitrate levels. While there has been limited research to prove the reduction amount, studies have shown that the ensiling process has been able to reduce the nitrate levels by almost half after the fermentation process has completed (Bustabad, unpublished).

Supplementation Of Conserved Forages

Even when feeding conserved forages, some producers are impacted by secondary challenges. Storage conditions, nutritive value, and cattle preferences are among challenges that producers are faced with each season (McCollum, 2025). Operations may run out of conserved forage due to weather conditions or improper storage, or operations with plenty of forage availability may have limited quality. Lack of proper forage quantity and quality may cause cattle performance to fall short of production goals if operations cannot meet nutritional needs. Seasonal and annual variation in forage quality can alter nutrient availability to grazing cattle, creating a need for supplementation when forage alone does not provide nutrients sufficient to support desired levels of animal performance (DelCurto et al., 2000). To fill nutritional gaps, supplementation can optimize productivity on various levels. Protein supplementation of cattle consuming low-quality forage has been shown to improve nutrient digestibility and nitrogen utilization, although responses depend on the amount and frequency of supplement

provided (Cappellozza et al., 2021). Common feedstuffs used to supplement cattle diets include whole cottonseed, cottonseed hulls, soybean meal, corn gluten feed, rice mill feed, and dried distillers' grains (Parish et al., 2023). When deciding how to supplement forages, it is recommended to complete a forage test to understand existing nutrient levels. Then, using the forage test and feed options that are readily available, the producer can decide how much supplement is needed.

Utilization Of Dried Distillers' Grains

Dried distillers' grains (DDG) are produced from cereal grains such as corn, barley, rye, sorghum, and wheat as a coproduct of the dry-grind ethanol industry. During ethanol production, starch is fermented by yeast to produce ethanol, which is subsequently removed by distillation. The remaining non-fermentable nutrients, including protein, fiber, fat, and minerals, are concentrated as the coproduct is dried to produce DDG (Rosentrater, 2018). Dried distillers' grains differ from dried distillers grains with solubles (DDGS) because DDGS contains condensed distillers solubles that are added back to the grain fraction before drying, and the addition of solubles can alter the nutrient composition and feeding characteristics of the resulting coproduct (Corrigan et al., 2009). Dried distillers' grains are commonly used as a cost-effective alternative to traditional protein supplements such as soybean meal in livestock diets. On average, DDG contains approximately 25–34% crude protein, 7–16% fat, and 18–47% neutral detergent fiber, making it a valuable source of both protein and energy for ruminants (Rosentrater, 2018). When included in forage-based cattle diets, the effects of DDG on intake and nutrient

utilization can depend on both the amount supplemented and the quantity of condensed distillers solubles incorporated into the coproduct (Corrigan et al., 2009).

Supplementing Dried Distillers Grains

Supplementing with DDG can be a cost-effective strategy for providing complementary nutrients to forage-based diets. Dried distillers' grains are an excellent source of energy, typically containing 85–95% total digestible nutrients, making them well suited to support the nutrient requirements of grazing cattle or cattle consuming conserved forages (Stewart et al., 2017). In addition to energy, DDG generally contains approximately 25–34% crude protein, although a substantial proportion of this protein is present as rumen-undegradable protein (RUP). Depending on the grain source and processing method, approximately one-half of the protein in DDG may escape ruminal degradation, allowing it to pass to the small intestine where digestible amino acids can be absorbed by the animal (Schingoethe et al., 2009; Stewart et al., 2017). This balance between rumen-degradable protein (RDP) and RUP makes DDG a valuable protein supplement in forage-based production systems. In forage-fed cattle, increasing DDG supplementation has been shown to increase total dry matter intake while decreasing forage intake, demonstrating that DDG can provide supplemental nutrients but may also partially substitute for forage as inclusion increases (Corrigan et al., 2009).

Dietary protein consumed by ruminants is partitioned into rumen-degradable protein and rumen-undegradable protein. Rumen-degradable protein is hydrolyzed by ruminal microorganisms into peptides, amino acids, and ammonia, which are utilized by microbes for microbial protein synthesis. As microbial cells pass from the rumen into the

abomasum and small intestine, they are digested and provide a major source of metabolizable protein to the animal (National Academies of Sciences, Engineering, and Medicine, 2016). In contrast, rumen-undegradable protein bypasses microbial degradation in the rumen and is digested enzymatically in the small intestine, where absorbable amino acids contribute directly to the animal's metabolizable protein supply (National Academies of Sciences, Engineering, and Medicine, 2016).

When high-nitrate forages are consumed, maintaining an active ruminal microbial population is essential because nitrate is sequentially reduced to nitrite and subsequently to ammonia by ruminal microorganisms. This reduction requires adequate fermentable energy and available nitrogen to support microbial growth and activity (Zhao et al., 2015). The ruminal response to nitrate may also depend on the composition of the fermentation substrate, as Lin et al. (2013) demonstrated that substrate fiber proportion and adaptation of rumen inoculum donors influenced *in vitro* nitrate disappearance and fermentation characteristics. Although much of the starch originally present in the grain is removed during ethanol production, DDG provides digestible fiber, protein, fat, and concentrated nutrients that complement forage-based diets. Therefore, the nutrient contribution of DDG and the influence of substrate composition on nitrate metabolism provide a biological rationale for evaluating DDG-containing mixtures with nitrate-containing forages; however, available evidence does not establish that DDG enhances nitrate reduction or detoxification. However, the present study did not directly evaluate nitrate metabolism or microbial protein synthesis; therefore, these mechanisms are

presented as biological explanations supported by previous research rather than direct outcomes of this experiment.

In Vitro Digestibility

Feeding trials are designed to create scientifically backed feeding recommendations for livestock producers, improving the operations' overall economic and production goals. Specifically, feed trials target ways for livestock farmers to find new nutritional, lower-cost options while partnering with the agricultural processing industry, which seeks to find ways to incorporate value-added products from the co-products after processing (Morrison 2012). However, there are some challenges associated with feeding trials, such as a larger risk associated with animal health, especially when dealing with potentially toxic feedstuffs, as well as obtaining a large sample population. Feeding trials are resource-intensive and require significant time, financial investment, and logistical planning (Rowlands 2025).

To address these barriers, researchers have implemented the use of in-vitro trials. These experiments are conducted in the laboratory, using samples collected from host animals. Samples are collected and then utilized in a laboratory. Digestibility studies performed in vitro have advantages such as short duration length, lower use of resources and labor, and less ethical concerns (Zou et al. 2023). Laboratory-based digestibility methods also allow multiple feedstuffs to be evaluated simultaneously under standardized incubation conditions, providing a practical approach for estimating the digestibility of ruminant feeds (Holden, 1999). An in vitro study consists of anaerobic fermentation using either rumen inoculum or enzymes that mimic the digestion of a sample, such as

feeds or forage (ANKOM). The ANKOM DaisyII system has been evaluated against conventional in vitro methods, with results demonstrating relatively good agreement for roughage feeds, although estimates may differ among certain concentrate and protein supplements (Mabjeesh et al., 2000). Methodological factors within the DaisyII system can also influence digestibility estimates, as sample mass within filter bags has been shown to affect measurements of neutral detergent fiber digestibility (Coblentz et al., 2019). Although in vitro methods provide a controlled approach for comparing feed substrates, resulting digestibility estimates should be interpreted within the limitations of the laboratory system and validated through in vivo research before conclusions regarding animal intake, health, or productive performance are made.

Benefits Of DDG Supplemented Operations

Meeting the nutrient requirements of beef cattle throughout growth, reproduction, gestation, and lactation is essential for optimizing animal performance and maintaining productive, profitable operations (NASEM, 2016). Because the nutritive value and availability of forage fluctuate throughout the year, supplemental feedstuffs are commonly incorporated into forage-based production systems to provide additional protein and energy when forage alone cannot meet animal requirements. Distillers grains have become an important coproduct feed in the beef industry because they supply concentrated protein, digestible fiber, fat, and phosphorus while providing an economical alternative to many conventional protein supplements (Klopfenstein et al., 2008). During ethanol production, most of the grain starch is removed through fermentation, concentrating the remaining nutrients and producing a feed ingredient that is relatively

low in starch and high in digestible fiber compared with the original grain (Schingoethe et al., 2009). Although much of the published literature has evaluated dried distillers' grains with solubles (DDGS), the nutrient characteristics of DDG similarly make it a suitable supplement for forage-based diets. In forage-fed steers, DDG has been successfully incorporated at increasing supplementation levels, although responses in forage intake and digestibility depended on both DDG inclusion rate and the proportion of condensed distillers solubles added to the coproduct (Corrigan et al., 2009).

Numerous studies have demonstrated that supplementation with distillers grains influence forage utilization without necessarily reducing overall nutrient intake. Loy et al. (2007) reported that supplementation with distillers grains decreased voluntary forage intake while maintaining total dry matter intake, illustrating a substitution effect in which supplemental nutrients partially replaced forage consumption. Similar responses were observed by Islas and Soto-Navarro (2011), who found that distillers grains supplementation altered forage digestion characteristics of grazing beef heifers, with responses dependent upon forage quality and supplementation level. More recently, Ciriaco et al. (2021) evaluated DDGS supplementation in steers consuming annual and perennial grass hays and reported that supplementation affected forage intake, ruminal degradation kinetics, and fermentation responses, although these effects differed according to forage type rather than supplementation alone. Collectively, these studies indicate that the response to distillers grains supplementation is influenced by interactions among supplement composition, forage quality, and dietary inclusion rate rather than by the supplement itself.

In addition to influencing forage intake, distillers grains have been shown to affect nutrient digestibility and ruminal fermentation. Previous in vitro work demonstrated that increasing inclusion of distillers grains in bermudagrass substrates increased substrate digestibility and altered fermentation characteristics, suggesting that coproduct supplementation can modify fermentation patterns under controlled conditions (Smith et al., 2020). Likewise, Adams et al. (2021) reported linear increases in total diet digestibility and decreases in forage dry matter intake as DDGS supplementation increased in growing heifers consuming bermudagrass hay, further supporting the substitution effect of distillers grains. However, responses to supplementation are not uniform. Niderkorn and Baumont (2009) demonstrated that associative effects between forages and supplemental feed ingredients may either enhance or depress fiber digestion depending on forage quality, nutrient composition, and supplement inclusion rate. Consequently, the effects of distillers grains cannot be generalized across forage systems, emphasizing the importance of evaluating supplementation strategies within specific forage substrates. Similarly, increasing DDG supplementation from 0 to 1.0% of body weight in steers consuming bermudagrass round-bale silage produced quadratic responses in total dry matter intake and total-tract apparent digestibility while decreasing forage intake, further demonstrating that responses to DDG depend on supplementation level (Smith et al., 2020).

Although the nutritional value of distillers grains and their influence on forage utilization have been well established, substantially less information is available regarding their use with high-nitrate forages. Nitrate metabolism in the rumen occurs

through the sequential microbial reduction of nitrate to nitrite and subsequently to ammonia, with the efficiency of this process dependent upon the ruminal environment and substrate availability (Zhao et al., 2015). Existing research has separately evaluated distillers grains supplementation and ruminal nitrate metabolism, but limited information is available regarding total-substrate digestibility when DDG is combined with sorghum–sudangrass differing in nitrate concentration under controlled in vitro conditions. This knowledge gap provided the rationale for the present study.

Conclusions

The rapidly changing costs of feed and other economic challenges facing livestock producers have increased the need for practical and cost-effective forage management strategies throughout the southeastern United States. Combined with seasonal forage shortages and variable environmental conditions, these challenges can limit producers' ability to meet livestock nutrient requirements while controlling production costs. Extending the grazing season, improving forage conservation, and strategically incorporating supplemental feedstuffs provide opportunities to address seasonal limitations in forage quantity and quality. Consequently, understanding the relationships among forage production, forage nutritive value, conservation practices, and supplementation is important for developing management strategies that efficiently utilize available feed resources.

Sorghum-sudangrass offers considerable potential as a warm-season forage because of its rapid growth, drought tolerance, adaptability, and high biomass production. Nitrogen fertilization can further increase forage production, although the response

depends on application rate and growing conditions (Beyaert and Roy, 2005). Additionally, the nutritive value and digestibility of sorghum-based forages can vary with maturity, genotype, and chemical composition, emphasizing the importance of considering forage characteristics when evaluating their nutritional value (Ledgerwood et al., 2009). Despite these advantages, nitrate accumulation under environmental stress or conditions of high nitrogen availability remains an important concern when sorghum-sudangrass is intended for livestock consumption. Management practices such as appropriate nitrogen fertilization, forage testing, harvest management, and conservation through ensiling can assist producers in managing forage quality and potential nitrate risk. Importantly, conservation should not be assumed to eliminate nitrate risk, and testing conserved forage remains necessary when elevated nitrate concentrations are suspected.

Supplementation provides another management option when available forage does not adequately meet livestock nutrient requirements. DDG can provide concentrated protein and energy to forage-based diets while offering an alternative use for coproducts of the ethanol industry. However, responses to distillers grains supplementation are not uniform across production systems. Supplementation can partially replace voluntary forage intake, and effects on digestion and ruminal fermentation depend on forage quality, supplement composition, and inclusion rate (Islas and Soto-Navarro, 2011; Smith et al., 2020). Furthermore, differences between DDG and DDGS should be considered when interpreting previous research because the addition of condensed distillers solubles can alter coproduct composition and feeding responses. Thus, the nutritional value of

DDG should be considered within the context of the complete diet rather than assuming that its inclusion consistently enhances digestion of the forage component.

The relationship between nitrate-containing forage and supplemental feed ingredients is particularly complex because ruminal responses depend on the chemical and microbial environment in which fermentation occurs. Nitrate is sequentially reduced by ruminal microorganisms through nitrite toward ammonia, and nitrate availability can alter microbial populations and fermentation characteristics (Zhao et al., 2015). Substrate characteristics can also influence nitrate metabolism; Lin et al. (2013) demonstrated that substrate fiber proportion and adaptation of rumen inoculum donors affected in vitro nitrate disappearance and fermentation responses. Similarly, interactions between forage and supplemental feed ingredients may produce positive, negative, or neutral associative effects depending on the chemical characteristics and proportions of the individual dietary components (Niderkorn and Baumont, 2009). Collectively, this literature indicates that neither nitrate concentration nor supplementation should necessarily be considered independently of the overall composition of the substrate being fermented.

In vitro digestibility systems provide a controlled method for initially investigating these relationships while reducing the resources required for animal feeding experiments. The ANKOM DaisyII system allows multiple feed substrates to be incubated simultaneously under standardized conditions and has been evaluated against conventional in vitro digestibility procedures (Holden, 1999; Mabjeesh et al., 2000). However, methodological factors, including inoculum source, sample preparation, sample mass, and incubation procedures, can influence resulting digestibility estimates

(Mabjeesh et al., 2000; Coblentz et al., 2019). Therefore, in vitro measurements are most appropriately interpreted as estimates of substrate digestibility under the specific conditions of the laboratory system and should not be considered direct measures of animal intake, nitrate toxicity, health, or productive performance.

Previous research has separately demonstrated effects of nitrogen fertilization and forage characteristics on sorghum-sudangrass production and composition (Beyaert and Roy, 2005; Ledgerwood et al., 2009), effects of distillers grains supplementation on forage-based diets (Islas and Soto-Navarro, 2011; Smith et al., 2020), and effects of nitrate and substrate characteristics on ruminal fermentation (Zhao et al., 2015; Lin et al., 2013). However, limited information is available regarding total-substrate digestibility when DDG is combined with sorghum-sudangrass differing in nitrate concentration under controlled in vitro conditions. Evaluating these substrates within the same incubation system provides an opportunity to characterize digestibility responses to forage category, DDG inclusion, and their interaction while recognizing that forage nitrate concentration may occur concurrently with differences in other chemical constituents.

Therefore, the objective of the present study was to evaluate the effects of forage nitrate category, DDG inclusion, and their interaction on the *in vitro* true digestibility of sorghum-sudangrass substrates using the ANKOM DaisyII incubation system. Specifically, sorghum-sudangrass representing four nitrate categories was evaluated either as forage alone or as a 50:50 forage–DDG mixture. This approach was designed to compare total-substrate IVTD among the experimental combinations rather than to determine whether DDG increased digestion of the sorghum-sudangrass fraction or

reduced nitrate toxicity. The resulting information provides a preliminary basis for further investigation of associative effects, nitrate metabolism, practical DDG inclusion rates, and the in vivo relevance of combining DDG with sorghum-sudangrass differing in nitrate concentration.

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CHAPTER TWO

THE EFFECT OF DDG SUPPLEMENTATION AND NITRATE LEVEL ON IN VITRO TRUE DIGESTIBILITY

Abstract

Sorghum–sudangrass (*Sorghum bicolor var. bicolor × bicolor var. sudanense)* hybrids are often used by livestock producers in the southeastern United States for their high forage yield, drought tolerance, and ability to grow under variable summer conditions. However, these forages are prone to nitrate accumulation under various environmental stressors or high nitrogen fertilization, creating potential risks to livestock. Concurrently, dried distillers' grains (DDG) remain a widely available, nutrient-dense by-product feed in Tennessee, offering both protein and energy supplementation for forage-based diets. Understanding how nitrate concentration and DDG supplementation interact to influence ruminal digestion is essential for optimizing feeding strategies. The objective of this study was to evaluate the in vitro true digestibility (IVTD) of sorghum–sudangrass harvested under four nitrate concentrations, as forage alone or as a 50:50 forage–DDG mixture.

Sorghum–sudangrass was grown under varying nitrogen fertilization rates (0 to 202 kg/ha) to produce forage with four nitrate concentrations (158, 517, 3,483, and 8,365 mg/kg). Forage samples were dried, ground, and assigned to one of two incubation substrates: (1) sorghum–sudangrass alone or (2) a 50:50 mixture of sorghum–sudangrass and dried distillers' grains (DDG). Samples were incubated in an ANKOM DaisyII incubator for 48 h using rumen fluid collected from a single fistulated cow maintained on a forage-based diet. Each treatment × nitrate concentration combination was represented by three independent jar-level experimental units (n = 3), with multiple filter bags within each jar serving as technical replicates. Treatments were distributed across incubation

runs, and incubation run was included as a blocking factor in the statistical analysis. Following incubation, in vitro true digestibility (IVTD) was determined gravimetrically. The 50:50 forage–DDG mixtures consistently exhibited greater IVTD than the forage-only substrates, with mean IVTD values ranging from 52.9% to 58.0%, whereas forage-only substrates ranged from 41.7% to 46.0%. No effect of forage nitrate concentration on IVTD was detected under the conditions of this study. Because the experiment compared forage-only substrates with 50:50 forage–DDG mixtures, these results indicate greater digestibility of the complete substrate rather than improved digestibility of the forage fraction alone. Furthermore, because nitrate disappearance, nitrite accumulation, microbial activity, and animal responses were not evaluated, the findings should not be interpreted as evidence that DDG altered nitrate metabolism or reduced nitrate toxicity. Although the inclusion of DDG reduced the nitrate concentration of the complete incubation substrate through dilution, this was a characteristic of the experimental design rather than a demonstrated feeding recommendation for high-nitrate forage.

Introduction

Sorghum-sudangrass (Sorghum x drummondii) is utilized by livestock producers in the Southeast for its drought tolerance, high forage yield, and adaptability to various summer growing conditions. These characteristics make sorghum-sudangrass an important forage resource that can thrive when cool-season forage growth is limited. However, the nutritive value of sorghum–sudangrass can vary considerably with plant maturity and hybrid characteristics. Ferreira et al. (2015) reported differences in crude protein, fiber composition, and in vitro digestibility among sorghum–sudangrass hybrids

and stages of maturity, demonstrating that forage digestibility is influenced by both plant development and chemical composition. The frequent occurrence of drought, excessive rainfall, and temperature fluctuations in the southeastern United States requires producers to adopt more intensive forage management practices. These environmental conditions can result in substantial variation in forage nitrate concentrations, ultimately influencing forage utilization and livestock performance. Environmental conditions that restrict plant growth can further influence nitrate accumulation in sorghum–sudangrass. George et al. (1971) demonstrated that nitrate accumulation in sorghum–sudangrass was influenced by light intensity, temperature, nitrogen fertilization, and stage of maturity, with prolonged low light and cool temperatures reducing dry matter production while increasing nitrate accumulation.

Nitrogen fertilization is a primary factor contributing to nitrate accumulation in sorghum–sudangrass, particularly when environmental stress limits plant growth and nitrate assimilation (Ball et al., 2015; Cassida, 2012). Elgersma et al. (2001) further demonstrated the relationship between nitrogen fertilization and nitrate accumulation in sorghum–sudangrass, reporting increased nitrate-N concentrations as nitrogen fertilization increased. The authors also observed differences in nitrate accumulation among harvests and plant portions, with lower concentrations in leaves and greater concentrations toward the lower portions of the stem. In addition to influencing nitrate accumulation, nitrogen fertilization can alter the overall nutritive composition of sorghum–sudangrass. Once consumed, nitrate undergoes microbial reduction in the rumen, first to nitrite and subsequently to ammonia, which can be utilized by rumen

microorganisms for microbial protein synthesis. Beyond its potential toxicity, nitrate can alter ruminal fermentation by affecting hydrogen utilization, fermentation end products, and microbial populations. Zhou et al. (2012) reported that nitrate concentration affected volatile fatty acid production and produced differential responses among ruminal microbial populations during in vitro fermentation, demonstrating that nitrate can influence fermentation characteristics in addition to its established role in nitrate toxicity. Özkan et al. (2023) reported that increasing nitrogen fertilization increased crude protein concentration and total digestible nutrients while decreasing neutral detergent fiber and acid detergent fiber concentrations in sorghum–sudangrass hybrids. These findings demonstrate that responses to nitrogen fertilization extend beyond nitrate accumulation and may result in concurrent changes in forage composition that influence nutritive value.

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Although elevated nitrate concentrations present management challenges for livestock producers, strategic supplementation may improve the utilization of forage-based diets. However, the effects of supplementation on ruminal fermentation and fiber digestibility depend on the nutrient composition, inclusion rate, and interactions between the supplement and the basal forage, resulting in positive, neutral, or negative associative effects (Niderkorn and Baumont, 2009). Loy et al. (2007) demonstrated that the effects of supplementation on forage utilization depend on the supplemental energy source. In ruminally cannulated heifers consuming a forage-based diet, DDGS supplementation decreased forage intake but increased total dry matter intake without reducing total-tract

NDF digestibility, whereas corn supplementation decreased forage intake and NDF digestibility. The response to distillers grains supplementation may also depend on the amount included in the diet. Islas and Soto-Navarro (2011) evaluated DDGS supplementation at 0, 0.2, 0.4, and 0.6% of body weight in beef heifers grazing small-grain pasture and reported a linear increase in NDF digestibility as DDGS supplementation increased. These findings demonstrate that the effects of distillers grains on forage-based diets are dependent on inclusion rate and provide evidence that DDGS can be incorporated without necessarily depressing fiber digestion. Similarly, Suarez-Mena et al. (2015) evaluated DDGS inclusion at 0, 7, 14, and 21% of dietary dry matter in diets containing different forage concentrations and demonstrated that the effects of DDGS on digestion and ruminal fermentation were influenced by both DDGS inclusion and the forage-to-concentrate ratio. These results further emphasize that responses to distillers grains should be interpreted in relation to both inclusion level and the composition of the basal diet. Distillers' grains provide a concentrated source of protein, digestible fiber, and energy and have been shown to maintain forage digestibility and support ruminal fermentation when included at appropriate levels in forage-based diets (Smith et al., 2017).

In vitro true digestibility (IVTD) is a widely accepted technique for evaluating the extent of ruminal degradation of forages and feed combinations under controlled laboratory conditions and serves as an efficient screening tool before conducting more resource-intensive in vivo studies (Foster et al., 2023). Holden (1999) compared the ANKOM DaisyII system with a conventional in vitro procedure and reported no

significant difference in dry matter digestibility estimates between methods, supporting the use of the DaisyII system for laboratory evaluation of feed digestibility. However, digestibility estimates differed among rumen-fluid inoculum sources, indicating that donor animal and inoculum characteristics can contribute to variation in in vitro digestibility measurements. Methodological factors within the DaisyII system can also influence estimates of digestibility. Coblentz et al. (2019) compared 0.25- and 0.50-g forage samples incubated in ANKOM F57 filter bags and reported greater in vitro NDF digestibility for the 0.25-g samples, particularly at 24-, 30-, and 48-hour incubation periods. These findings demonstrate that sample size and incubation conditions should be considered when interpreting digestibility estimates obtained using the DaisyII system. Although previous studies have evaluated distillers' grains supplementation and forage nitrate accumulation independently, little information is available regarding the interaction between forage nitrate concentration and DDG supplementation on IVTD. Therefore, evaluating IVTD of forage–DDG mixtures across a range of nitrate concentrations may improve our understanding of how DDG supplementation influences the utilization of high-nitrate forage substrates.

Materials and Methods

Experimental Design

Experimental procedures were approved by the University of Tennessee Institutional Animal Care and Use Committee (Protocol No. 3134-1225). The study was conducted as a 2 × 4 factorial arrangement of treatments in a randomized complete block design, with two supplementation treatments (DDG or no DDG) and four sorghum–

sudangrass nitrate concentrations as fixed effects. Initial sorghum–sudangrass nitrate concentrations were 158, 517, 3,483, and 8,365 mg/kg DM, hereafter referred to as TRACE, LOW, MED, and HIGH, respectively. Treatment combinations were represented by three independent jar-level experimental units (n = 3) distributed across ANKOM DaisyII incubation runs, with incubation run serving as the blocking factor. The experimental unit was the ANKOM DaisyII incubation jar. Each jar contained 12 ANKOM F-57 filter bags representing technical replicates of a single supplementation × nitrate concentration combination, and each jar contained only one treatment combination during an incubation run. One empty correction-factor bag was included in each jar during every run. Following incubation, IVTD was calculated for each filter bag, and the 12 bag values within a jar were averaged to obtain a single jar-level IVTD observation. These jar means constituted the final dataset used for statistical analysis, resulting in three independent observations for each supplementation × nitrate concentration combination (24 jar-level observations total).

Preparation of Forage and DDG Samples

The experiment was conducted in the University of Tennessee Brehm Animal Science Nutrition Lab located in Knoxville, TN. Forage samples were obtained from the Mason Lab after being harvested at the Northeast Tennessee AgResearch and Education Center (NETREC) (36°06' N and 82°50' W, 409.9 m asl) located in Greeneville, TN. The forage samples were obtained from field plots under a randomized complete block design with 5 N fertilizer treatments 0, 50, 100, 150, and 200 kg N/ha with 3 replicates. The forage samples under treatment “0” kg N/ha were not used in the current trial. Post

harvest in the summer of 2024, forage samples were dried at 55°C for 72 hours, processed using a Wiley Mill (Thomas-Wiley Laboratory Mill Model 4, Arthur H. Thomas Co. Philadelphia, PA) to pass through a 2mm screen, followed by the cyclone sample mill (Foss Cyclotec, Foss North America, Eden Prairie, MN) that had a 1mm screen. Samples were analyzed via NIRS to determine nutritive values. Average values of nutritive value constituents can be found in Table 1. To obtain final nitrate levels, the forage samples were sent to The UT Soil, Plant, and Pest Center (Nashville, TN) for wet chemistry.

Table 1: SORGHUM-SUDANGRASS NUTRITIVE VALUE CONSTITUENT AVERAGES

Nitrate Level	**CP (%)**	**ADF (%)**	**NDF (%)**	**TDN (%)**	**Starch (%)**	**NSC (%)**	**Ca (%)**	**P (%)**	**K (%)**	**Mg (%)**
TRACE	9.0	38.4	63.8	58.4	1.3	2.0	0.43	0.53	1.41	0.17
LOW	10.3	38.2	62.3	58.6	1.1	1.9	0.53	0.27	1.42	0.21
MED	15.2	36.7	59.7	60.2	0.7	1.8	0.71	0.31	1.70	027
HIGH	16.2	37.7	60.5	59.2	0.7	1.8	0.67	0.32	1.49	0.28

The DDG was obtained from the Tennessee Farmers Co-op (Rockford, TN) and ground using a Wiley mill to pass through a 2-mm screen. The sample was analyzed in the University of Tennessee Forage Testing Laboratory using near-infrared reflectance spectroscopy (NIRS) to determine its nutritive value. On a dry matter basis, the DDG contained 6.9% crude fat, 25.2% crude protein, 8.8% moisture (as received), and 7.8% crude fiber. The ANKOM DaisyII procedure specifies the total sample weight per filter bag (0.50 g) but does not prescribe the proportion of individual feed ingredients within the substrate. Therefore, a 50:50 sorghum–sudangrass:DDG substrate mixture was

selected to evaluate the effects of DDG inclusion on in vitro true digestibility while maintaining a constant sample weight across treatments. Similar forage-to-distillers' grains ratios have been used in previous in vitro fermentation studies evaluating the effects of distillers' grains on forage digestibility (Smith et al., 2020). Sample bags assigned to the DDG treatment contained 0.25 g of sorghum–sudangrass and 0.25 g of DDG, whereas sample bags assigned to the no-DDG treatment contained 0.50 g of sorghum–sudangrass. Samples were placed into labeled ANKOM F-57 filter bags, heat-sealed, assigned to their respective incubation jars, soaked in acetone to remove the manufacturing surfactant, air-dried, and weighed to obtain the initial bag weight (W1). After sample addition, the filled bags were reweighed, and the recorded weight was designated as W2.

Collection of Rumen Fluid

Rumen fluid was collected from a crossbred cannulated cow housed at the University of Tennessee Veterinary Research and Education Center. The cow had ad libitum access to mixed pasture, water, and hay throughout the study and maintained an appropriate body condition score with no signs of illness. Rumen fluid collections occurred every 48 hours over a 12-day period to provide inoculum for each DaisyII incubation run. Collections occurred in the morning hours, from 8 AM to 12 PM. The cow was brought into the handling facility using low-stress handling techniques and restrained using a chute system and headgate. The rubber cap of the cannula was removed, and the plastic tubing attached to the siphon was used to manually remove rumen inoculum. The cannula seal was cleaned off to remove rumen digesta, and the

rubber lid was securely placed back into the cannula without incident. Once collection was complete, the cow was released from the chute system and brought back to the herd. Collection notes were obtained, including date, time, and name of approved personnel collecting, to ensure proper IACUC records. The inoculum was collected and stored in an insulated 2-L thermos. Prior to the sample collection, the thermos was filled with hot DI water to ensure the sample temperature was maintained. The collection resulted in 2 liters of rumen inoculum, not including digesta material. Inoculum was transported to the lab immediately for further processing and was in the DaisyII incubator within 30 minutes of collection. Collection material was filtered in the lab using 4 layers of cheesecloth before completing any further steps. Following filtration, two 15 mL aliquots of rumen fluid were transferred into separate 15 mL centrifuge tubes and stored at −30 °C for future microbial and metabolite analyses. These samples were archived for future research and were not analyzed as part of the present study.

Batch Culture in Daisy II Incubator

To prepare the DAISYII incubator jars, a buffer solution was prepared by mixing the reagents listed in the "In Vitro True Digestibility using the ANKOM DAISYII Incubator" procedure (ANKOM). Reagents for solution A included KH_2PO_4, $MgSO_4 \cdot 7H_2O$, NaCl, $CaCl_2 \cdot 2H_2O$, and urea. While solution B included Na_2CO_3 and $Na_2S \cdot 9H_2O$. The final solution had a 1:5 A:B ratio and was adjusted to a final pH of 6.8. Once reagents were mixed and completely dissolved in water, 1600 mL of buffer solution was added to each of the four jars along with 400 mL of filtered rumen inoculum. The samples were incubated for 48 hours at 39 ◦ rotating throughout the entire duration. Upon

completion of the 48-hour digestion, samples in each jar were rinsed with cool water, then carefully drained and gently squeezed to remove the bulk of the digestive solution and water-soluble compounds. Sample bags were placed in a zip-top bag, appropriately labeled, and stored in the freezer until the final rinse.

ANKOM 2000 Fiber Analyzer

Sample bags were removed from the freezer and rinsed with warm distilled water for separation. Sample bags were placed in bag suspender trays, with an empty tray on top. Trays were stacked on the center post of the suspender, with each level rotated 120 degrees relative to the tray below it. The drain hose was placed into an acid wash sink, and the drain valve was closed prior to the start of each run. Neutral Detergent Solution was added in the amount of 1.8 L to ensure the bag suspender tray was completely submerged. Alpha-amylase was added in the amount of 4.0 mL; the vessel lid was closed and secured. The ANKOM$_{2000}$ Fiber Analyzer ran for two hours at 70 °C to provide a final rinse of samples.

After two hours, the machine was turned off, the drain valve was opened, and the vessel lid was opened. Once completely drained, the valve was closed, alpha-amylase in the amount of 4.0mL was added along with enough warm DI water to cover the suspension trays, and without turning on the heat source, the machine was turned on to complete a rinse. After three minutes, the solution was drained, and this step was repeated once more with 4.0 mL of alpha-amylase and then once with distilled water only. When the rinses procedure was complete, sample bags were gently squeezed to remove excess liquid and then placed in acetone to completely cover the bags for 5

minutes. Samples were laid flat on a metal tray and flipped every 30 minutes to allow the acetone to completely evaporate before being placed in the oven at 102 ± 2 °C for 2 hours. After being removed from the oven, samples were placed directly into a large zip-top bag with a desiccant pouch and left to cool to room temperature.

IVTD Calculation

After incubation, the sample bags were allowed to cool to room temperature before being weighed to obtain the final bag weight (W3). The recorded values for W1, W2, and W3, together with the correction factor bag weights for each incubation jar, were used to calculate in vitro true digestibility (IVTD) using the equation described in the ANKOM DaisyII procedure (ANKOM Technology, 2017).

% IVTD (as-received basis) = 100 - (W3 – (W1 x C1)) x100 /W2

W1 = Bag tare weight

W2 = Sample weight

W3 = Dried weight of bag with fiber after extraction process

C1 = Blank bag correction

Statistical Analysis

Data were analyzed using a two-way factorial analysis of variance (ANOVA) in R version 4.4.2 (R Core Team, 2024). Fixed effects included supplementation (DDG or no DDG), nitrate concentration (TRACE, LOW, MED, and HIGH), and their interaction. The response variable was in vitro true digestibility (IVTD, %). Statistical significance was declared at $P < 0.05$. Following a significant ANOVA, pairwise comparisons among

treatment means were performed using Tukey's Honestly Significant Difference (HSD) adjustment with the emmeans package (Lenth, 2024).

Results

Results indicated that DDG supplementation significantly affected in vitro true digestibility (IVTD) of the substrates ($P < 0.001$), whereas nitrate level ($P = 0.471$) and the supplementation × nitrate level interaction ($P = 0.252$) were not significant. Mean IVTD values are presented in Table 2. Across all nitrate concentrations, the forage–DDG mixtures exhibited greater IVTD (52.9–58.0%) than the forage-only treatments (41.7–46.0%). The lowest IVTD was observed in the forage-only TRACE treatment, whereas the highest IVTD was observed in the forage–DDG HIGH treatment.

Residual diagnostics indicated a departure from normality based on the Shapiro–Wilk test ($W = 0.7866$, $P < 0.001$). Prior to the final statistical analysis, two ANKOM F-57 filter bags were excluded because of documented sealing failures that compromised sample retention. Both exclusions occurred during Run 1; one bag was removed from Jar 1 in the DDG × TRACE treatment combination, and one bag was removed from Jar 4 in the NO DDG × LOW treatment combination. The bags were excluded based on physical evidence of unsuccessful sealing rather than on the magnitude of their IVTD values. Following exclusion, each affected jar contained 11 usable technical-replicate bags, whereas unaffected jars retained 12. The remaining bag-level IVTD values within each jar were averaged to obtain the jar-level response used in the final statistical analysis. A sensitivity analysis retaining the two technically compromised observations produced slightly greater treatment means and resulted in a significant DDG × nitrate interaction;

in contrast, no significant interaction was detected after the two failed bags were excluded. The exclusion-based model was retained as the final analysis because the two observations were associated with documented procedural failures and were therefore not considered valid measurements of substrate digestibility. Residuals remained non-normal following exclusion; consequently, the results were interpreted with consideration of the assumption violation, the sensitivity of the interaction inference to the two exclusions, and the limited number of independent jar-level experimental units. Tukey's honestly significant difference (HSD) test was used for post hoc comparisons, and treatment-combination IVTD values from the final analysis are presented in Figure 1.

Table 2:IVTD% OF SUPPLEMENTED AND NON-SUPPLEMENTED SORGHUM SUDANGRASS

Supplementation	IVTD %
DDG	54.9[a]
NO DDG	42.7[b]

($p<0.05$, SEM: Standard Error of the Mean =1.8, N=3)

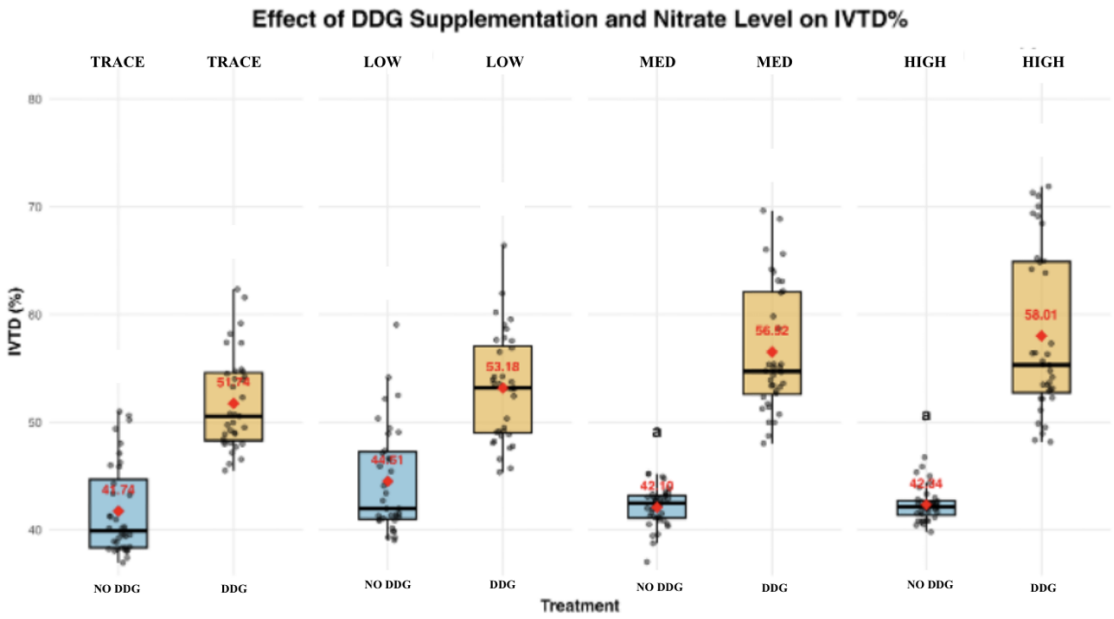

Figure 1:IVTD% OF SUPPLEMENTED AND NON-SUPPLEMENTED SORGHUM-SUDANGRASS AT VARYING NITRATE LEVEL

Discussion

The present study demonstrated that 50:50 sorghum–sudangrass–DDG substrate mixtures exhibited greater measured in vitro true digestibility than forage-only substrates, whereas nitrate concentration and the DDG × nitrate concentration interaction did not significantly affect IVTD. Because digestibility was measured for the complete substrate rather than the forage fraction alone, these findings should be interpreted as differences in total-substrate IVTD rather than evidence that DDG increased the digestibility of the sorghum–sudangrass component. Previous research has reported variable responses to distillers grains inclusion in forage-based diets, with responses influenced by forage quality, diet composition, and supplement inclusion rate. Loy et al. (2007) reported that

distillers grains supplementation reduced forage intake while maintaining total nutrient intake in beef cattle, whereas Islas and Soto-Navarro (2011) observed that responses to distillers grains supplementation varied according to forage quality and supplementation level. Similarly, Smith et al. (2020) reported differences in in vitro digestibility and fermentation responses among bermudagrass substrates containing increasing concentrations of distillers grains, further demonstrating that responses to distillers grains depend on substrate composition and dietary inclusion rate. Collectively, these studies indicate that the effects of distillers grains cannot be generalized across forage systems and should be interpreted within the context of the forage substrate and experimental conditions evaluated. Accordingly, the greater measured IVTD observed in the present study should be interpreted as the digestibility of the complete 50:50 forage–DDG substrate under controlled in vitro conditions rather than evidence of improved digestibility of the sorghum–sudangrass component alone.

The greater measured IVTD observed for the 50:50 forage–DDG substrate mixtures in the present study is consistent with the findings of Smith et al. (2020), who reported that increasing inclusion of dried distillers' grains with solubles (DDGS) in bermudagrass substrates increased the measured in vitro true digestibility of the complete forage–DDGS mixtures compared with forage alone. However, Smith et al. similarly evaluated the digestibility of mixed substrates rather than the forage fraction independently and, therefore, did not demonstrate improved digestibility of the forage component or a positive associative effect between forage and DDGS. Although the present study evaluated DDG rather than DDGS, both studies indicate that replacing

approximately one-half of the forage substrate with a distillers grain coproduct resulted in greater measured IVTD of the complete substrate under controlled in vitro conditions. Because the present experiment did not include a DDG-only treatment, it was likewise not possible to distinguish the contribution of DDG digestibility from potential associative effects between DDG and sorghum–sudangrass. Consequently, the greater measured IVTD observed in the present study should be interpreted as a response of the complete forage–DDG mixture rather than evidence that DDG improved digestibility of the sorghum–sudangrass component itself.

Although the present study evaluated in vitro digestibility rather than animal performance, the findings may have relevance to forage-based production systems. Griffin et al. (2012) summarized results from 20 studies evaluating distillers grains supplementation in beef cattle and reported improvements in average daily gain and final body weight while demonstrating that distillers grains partially replaced forage intake within the diet. Because Griffin et al. evaluated production performance rather than in vitro true digestibility (IVTD), direct comparisons with the present study should be made cautiously. Nevertheless, their findings support a possible role for DDG inclusion in forage-based production systems and provide broader production context for future in vivo investigations evaluating whether the greater total-substrate IVTD observed under controlled laboratory conditions translates into improved animal performance.

The greater measured in vitro true digestibility (IVTD) observed for the 50:50 forage–DDG substrate mixtures is consistent with previous studies

evaluating distillers grains in forage-based systems. Smith et al. (2020) reported that increasing inclusion of dried distillers grains with solubles (DDGS) in bermudagrass substrates increased the measured IVTD of the complete forage–DDGS mixtures compared with forage alone, although the authors similarly evaluated mixed substrates rather than the forage fraction independently. Likewise, Loy et al. (2007) and Islas and Soto-Navarro (2011) demonstrated that responses to distillers grains supplementation varied according to forage quality, diet composition, and supplementation level, indicating that responses to distillers grains cannot be generalized across forage systems. The nutritional characteristics of distillers grains described by Schingoethe et al. (2009), including greater concentrations of crude protein, digestible fiber, and energy than the original grain following starch removal during ethanol production, provide a plausible biological basis for these responses. However, because digestibility in the present study was measured for the complete 50:50 forage–DDG substrate rather than the sorghum–sudangrass fraction alone, the greater measured IVTD should not be interpreted as evidence that DDG improved digestibility of the forage component itself. Instead, the observed response is equally consistent with the inherently greater digestibility and lower fiber concentration of the mixed substrate. Alternatively, associative effects between DDG and sorghum–sudangrass may have contributed to the response, although the present experimental design, including the absence of a DDG-only treatment, did not allow these possibilities to be distinguished. In addition, previous research has shown that excessive dietary fat and sulfur

associated with high inclusion rates of distillers grains may negatively affect ruminal fiber digestion and animal performance (Schingoethe et al., 2009; Klopfenstein et al., 2008), emphasizing that responses to distillers grains are dependent on diet composition and inclusion rate. Consequently, the biological mechanisms responsible for the greater measured IVTD observed in the present study remain speculative because microbial populations, ruminal pH, volatile fatty acid production, microbial protein synthesis, and fiber-specific degradation were not measured. Future studies incorporating these measurements, together with multiple DDG inclusion rates and a DDG-only treatment, are needed to distinguish the effects of substrate composition from potential associative effects and to determine the mechanisms underlying the greater total-substrate IVTD observed in this study.

Although the highest numerical IVTD values were observed for the 50:50 forage–DDG substrate mixtures containing the MED and HIGH nitrate concentrations, no significant effect of nitrate concentration or DDG × nitrate concentration interaction was detected. Therefore, these numerical differences should not be interpreted as evidence that DDG becomes more effective as forage nitrate concentration increases. Rather, under the conditions of the present study, no evidence was detected that the response of total-substrate IVTD differed among the nitrate concentrations evaluated. Because each treatment combination was represented by only three independent incubation jars, the statistical power to detect relatively small differences among nitrate concentrations or interaction effects was limited. Consequently, modest biological differences cannot be

excluded, and additional research using a greater number of independent experimental units would be required to more precisely evaluate potential interactions between forage nitrate concentration and DDG inclusion.

No significant differences in IVTD were detected among the four forage nitrate categories evaluated in this study. However, nitrate concentration was not independently manipulated because the forage categories were produced using different nitrogen fertilization treatments. Consequently, the resulting forages differed not only in nitrate concentration but also in crude protein, neutral detergent fiber, mineral concentrations, and potentially other compositional characteristics. These differences confound the interpretation of nitrate as an independent factor and prevent changes in IVTD from being attributed specifically to forage nitrate concentration. Therefore, the present results demonstrate only that no differences in measured IVTD were detected among the four forage categories under the conditions of this in vitro experiment. Additional studies in which nitrate concentration is manipulated independently of forage composition would be necessary to determine the specific effect of nitrate concentration on substrate digestibility.

Overall, the present study provides a preliminary evaluation of total-substrate in vitro true digestibility (IVTD) in forage-only substrates and 50:50 sorghum–sudangrass–DDG mixtures across four chemically different forage categories. The forage–DDG mixtures exhibited greater measured IVTD than the forage-only substrates, while no significant differences in IVTD were detected among the four forage categories or for the DDG × forage category interaction. Because the forage categories were generated

through different nitrogen fertilization treatments and differed in nitrate concentration as well as other chemical characteristics, the effects of nitrate could not be isolated from differences in forage composition. Additionally, the use of mixed substrates and the absence of a DDG-only treatment prevented determination of whether the greater IVTD of the forage–DDG mixtures resulted from the inherent digestibility of DDG, associative effects between DDG and forage, or a combination of these factors. Therefore, these findings should not be interpreted as evidence that DDG enhanced digestion of the sorghum–sudangrass fraction or mitigated the effects of nitrate. Rather, this study establishes a preliminary jar-level comparison of total-substrate IVTD that can inform future experiments designed to independently evaluate nitrate concentration, DDG inclusion rate, forage composition, and potential associative effects.

Limitations

Several limitations of the experimental design should be considered when interpreting the results of this study. First, the experiment compared forage-only substrates with 50:50 forage–DDG mixtures rather than evaluating DDG as a conventional supplementation treatment. Because DDG replaced one-half of the forage substrate, the nitrate concentration of each mixed substrate was inherently diluted relative to the corresponding forage-only substrate. Additionally, the absence of a DDG-only treatment prevented separation of the inherent digestibility of DDG from potential associative effects between DDG and sorghum–sudangrass. Therefore, the greater measured in vitro true digestibility (IVTD) of the 50:50 forage–DDG mixtures cannot be

interpreted as evidence that DDG increased digestibility of the sorghum–sudangrass fraction or mitigated the effects of forage nitrate.

Interpretation of the nitrate response was further limited by differences in forage composition among the four forage categories. The sorghum–sudangrass categories were produced using different nitrogen fertilization treatments and consequently differed not only in nitrate concentration but also in crude protein, neutral detergent fiber, mineral concentrations, and potentially other chemical characteristics. Nitrate concentration was therefore not manipulated independently of forage composition, preventing the effects of nitrate from being isolated from other compositional differences among the forages. Furthermore, forage was obtained from a single growing season and production location. Sampling across multiple years, harvests, and locations would capture greater variation in forage composition and environmental conditions and allow a more comprehensive evaluation of the relationships among forage composition, nitrate concentration, and substrate digestibility.

Additional limitations were associated with the in vitro system and experimental replication. Rumen inoculum was collected from a single fistulated cow, limiting representation of biological variation among donor animals. Incubation run was incorporated into the statistical model as a blocking factor; however, each treatment combination was represented by only three independent jar-level experimental units. The 12 filter bags within each jar represented technical replicates and did not constitute independent experimental units. Consequently, the limited number of independent jars reduced statistical power to detect smaller forage-category or DDG × forage-category

effects. Accordingly, nonsignificant effects should be interpreted as no effects detected under the conditions of this experiment rather than evidence of equivalence among treatments. Bag failures and preparation errors also produced outlying observations, and the IVTD data did not meet the assumption of normality. These factors introduce additional uncertainty into the estimated treatment responses and should be considered when interpreting the results.

Finally, the experiment evaluated only one DDG inclusion rate and IVTD as the primary response variable. The 50:50 forage–DDG mixture represented an experimental substrate ratio and should not be interpreted as equivalent to a specific practical feeding rate in livestock. Measurements of nitrate disappearance, nitrite accumulation, ruminal pH, microbial populations, volatile fatty acid production, microbial protein synthesis, feed intake, nutrient absorption, animal health, and animal performance were not included in the present study. Therefore, the experiment cannot establish the mechanisms responsible for the observed IVTD response, determine nitrate detoxification or safety, or predict responses to DDG inclusion under production conditions. Future research incorporating a DDG-only treatment, multiple practical DDG inclusion rates, independently manipulated nitrate concentrations, multiple rumen-fluid donors, greater jar-level replication, and in vivo measurements is needed to distinguish the effects of substrate composition from potential associative effects and to support the development of practical feeding recommendations.

Conclusions

The 50:50 forage–DDG substrate mixtures exhibited greater measured in vitro true digestibility (IVTD) than forage-only substrates across the nitrate concentrations evaluated. The main effect of DDG inclusion was significant ($P < 0.001$), whereas nitrate concentration ($P = 0.471$) and the DDG × nitrate concentration interaction ($P = 0.252$) were not significant. However, because IVTD was measured for the complete substrate rather than the forage fraction alone, these findings should not be interpreted as evidence that DDG improved the digestibility of sorghum–sudangrass itself. Furthermore, the 50:50 forage–DDG mixtures inherently diluted the nitrate concentration of the complete substrate, and the absence of a DDG-only treatment prevented separation of the effects of DDG digestibility from potential associative effects between DDG and sorghum–sudangrass. Consequently, additional in vivo research is warranted to evaluate practical DDG inclusion rates, nitrate metabolism, ruminal fermentation, animal performance, and associative effects before management recommendations can be developed. Despite these limitations, the present study establishes a foundation for future investigations evaluating DDG inclusion in forage-based diets containing varying nitrate concentrations.

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CHAPTER THREE

FORAGE RELATED NEEDS OF TENNESSEE SMALL RUMINANT PRODUCERS

Abstract

By engaging with small-ruminant producers across Tennessee, this project identified forage-related educational priorities and highlighted opportunities for future Extension programming. An online needs assessment survey was conducted during November 2025 and distributed through multiple social media platforms accessible to small-ruminant producers. The survey consisted of 13 questions, including 11 demographic questions, one Likert-type rating matrix containing 11 forage-related educational topics, and one optional open-ended question. Respondents rated their level of interest in each forage topic using a five-point Likert-type scale, where 1 indicated the least interest and 5 indicated the greatest interest. The survey received 201 total responses, of which 182 met the Tennessee eligibility criteria. Among eligible respondents representing 68 Tennessee counties, the largest demographic groups were female (52%), 45–54 years of age (27%), and producers with 10 or more years of small-ruminant production experience (30%). Of the 11 educational topics evaluated, the highest mean ratings were observed for extending the grazing season (4.47), hay and forage quality (4.32), forage-related health problems (4.28), and pasture assessment (4.24). These findings provide direction for the continued development of the University of Tennessee Master Small Ruminant Program by identifying forage management topics of greatest interest among survey respondents and informing the development of future educational resources.

Introduction

Small ruminant production has become an increasingly important component of U.S. animal agriculture, with sheep and goats contributing to meat, milk, fiber, and breeding-stock production across diverse production systems (Miller and Lu, 2019). Sheep and goats are recognized for their ability to efficiently utilize low-quality feedstuffs, browse, and forage resources while maintaining productive performance under a wide range of environmental conditions (Animut et al., 2005). As consumer demand for sheep and goat products has increased, producers have expanded and diversified their operations to meet market demands (Escareño et al., 2013). Feed remains one of the largest production expenses in sheep and goat enterprises, making efficient forage utilization essential for improving both profitability and long-term sustainability (Niderkorn and Baumont, 2009). In the southeastern United States, forage-based production systems rely on a combination of warm- and cool-season forages to provide grazing opportunities throughout much of the year; however, seasonal variation in forage availability and quality continues to create management challenges for producers (Animut et al., 2005). Consequently, understanding producers' forage management needs is critical for developing research-based educational programs that improve forage utilization and support sustainable small-ruminant production systems (Whaley et al., 2022).

With forage serving as the foundation of most small-ruminant production systems, effective forage management directly influences pasture productivity, forage quality, animal performance, and overall farm profitability. Producers must make

management decisions regarding pasture establishment, forage species selection, grazing management, soil fertility, hay quality, and seasonal forage availability while adapting to changing environmental conditions and increasing production costs. Drought, excessive rainfall, declining pasture quality, and fluctuating fertilizer costs further complicate forage management decisions, increasing the need for timely, research-based educational resources that assist producers in making informed management decisions (Lemus & Brown, 2021).

Extension serves an important role in translating scientific research into practical management recommendations for agricultural producers. To ensure educational programming reflects stakeholder priorities, Extension systems frequently use formal needs assessments to identify knowledge gaps, prioritize educational topics, and allocate educational resources effectively (Caravella, 2006). Producer-driven needs assessments have been shown to improve Extension programming by ensuring educational materials address topics identified as most relevant by stakeholders rather than perceived needs of educators (Al-Mazroa Smith & Miller, 2024). By incorporating producer input into program development, Extension educators can better develop educational resources that improve program participation, producer engagement, and adoption of recommended management practices.

Previous producer needs assessments have evaluated educational priorities among sheep and goat producers throughout the United States. Whaley et al. (2022) surveyed U.S. sheep and goat producers and identified parasite management, nutrition, and reproductive management as the highest educational priorities. Their study demonstrated

the value of systematically identifying producer needs to guide future Extension programming. However, forage-related educational priorities were evaluated only broadly, leaving limited information regarding the specific forage management topics most important to sheep and goat producers within Tennessee and the southeastern United States. Because forage systems differ considerably across geographic regions, regional assessments are needed to identify educational priorities that reflect local environmental conditions, production practices, and producer needs.

The University of Tennessee provides forage education through programs such as the Master Small Ruminant Program and the Beef and Forage Center. During the 2025 Master Small Ruminant Program, forage-related sessions consistently generated more producer discussion and questions than many other educational topics. Although these observations suggested substantial producer interest in forage management, they did not objectively identify which forage topics producers considered most important or where educational gaps existed. Therefore, a formal forage-related needs assessment was conducted to systematically identify forage educational priorities among Tennessee sheep and goat producers. The objective of this study was to identify forage-related educational needs, characterize the demographics of survey respondents, and provide producer-driven information to guide future Extension programming and educational resource development within the Tennessee Master Small Ruminant Program.

Materials and Methods

Survey Design

The objective of this study was to identify forage-related educational priorities among Tennessee sheep and goat producers and provide producer-driven information to guide future University of Tennessee Extension programming. A cross-sectional online needs assessment was developed using Qualtrics XM (Qualtrics, Provo, UT, USA) during October 2025. The survey was designed in collaboration with the University of Tennessee Small Ruminant Extension Specialist to ensure that the educational topics reflected current and emerging forage management issues relevant to sheep and goat producers throughout Tennessee.

To encourage participation while minimizing respondent burden, the survey consisted of 11 total questions designed to collect demographic information and assess producer interest in forage-related educational topics. The survey instrument was reviewed by the University of Tennessee Small Ruminant Extension Specialist prior to distribution to ensure the questions were appropriate for the intended audience. A formal pilot test of the survey was not conducted. Because the survey was developed as an Extension needs assessment to identify educational priorities, data analysis was limited to descriptive statistics rather than hypothesis testing.

Target audience

The target population consisted of sheep and goat producers residing in Tennessee. Producers from outside Tennessee who followed the University of Tennessee Small Ruminant Extension program or utilized its educational resources were also able to

participate; however, only responses submitted by Tennessee residents meeting the study inclusion criteria were included in the final analysis. Responses originating from outside Tennessee were retained separately for future Extension reference but were excluded from the results presented in this study.

Distribution and Participation

The survey was administered during November 2025 and distributed electronically through University of Tennessee Extension communication channels. The survey link was initially posted on the University of Tennessee Small Ruminant Extension Facebook page and subsequently shared by Extension personnel, producers, and the primary investigators through social media. In addition, producers who had previously participated in the Master Small Ruminant Program or registered for previous University of Tennessee Extension educational programs received the survey through existing email distribution lists. Participation was voluntary and anonymous, and no incentives were offered for survey completion.

Content

The survey instrument consisted of multiple demographic questions, one Likert-type rating matrix, and one open-ended question. Demographic questions collected information on state of residence, county, age, gender, race, ethnicity, sheep and/or goat ownership, primary production enterprise, years of small-ruminant production experience, herd size, and breeds raised. The Likert-type rating matrix consisted of 11 forage-related educational topics, with respondents asked to rate their level of interest using a five-point scale ranging from 1 (least interested) to 5 (most interested). The

educational topics included weed control, poisonous plants, hay and forage quality, forage testing, soil testing, rotational grazing, stocking density, extending the grazing season, pasture assessment, mixed-species grazing, and forage-related health problems. The survey concluded with one optional open-ended question that allowed respondents to identify additional forage-related educational topics not represented in the rating matrix.

Data Collection

Survey responses were exported directly from Qualtrics XM into Microsoft Excel (Microsoft Corporation, Redmond, WA, USA) for data management and analysis. Responses were reviewed prior to analysis to determine eligibility for inclusion in the study. Eligible responses consisted of complete surveys submitted by Tennessee residents. Responses were excluded if they originated from outside Tennessee, were incomplete, or did not include responses to the forage education priority question. Excluded responses were retained separately for future Extension reference but were not included in the analyses presented in this study. Because survey responses were anonymous, duplicate submissions could not be definitively identified. The final dataset consisted of complete responses that met the predetermined inclusion criteria.

Data Analysis

Descriptive statistics were calculated using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA). Frequencies and percentages were calculated for demographic variables to describe the survey population. Interest in each forage-related educational topic was summarized using mean Likert-type scores, calculated by averaging respondent ratings for each educational topic. Mean scores were then ranked

from highest to lowest to identify forage management topics receiving the greatest level of interest among respondents.

Responses to the open-ended question were reviewed qualitatively and organized into common themes based on recurring educational topics. The responses did not identify additional forage-related educational needs beyond those captured in the structured survey questions and, therefore, were not summarized further.

Results

The survey closed on November 30, 2025, with 201 total responses. Responses submitted by individuals residing outside Tennessee (n=5) were excluded from further analysis. An additional 14 Tennessee responses were excluded because the survey was incomplete and did not meet the study inclusion criteria. The final analytical dataset consisted of 182 Tennessee respondents representing 68 counties, providing broad geographic representation of sheep and goat producers across the state.

Producer demographics provided important context for interpreting the survey findings. Among respondents, 52% identified as female, 46% identified as male, and 2% selected "prefer not to say." The largest age category was 45–54 years (27%), although respondents represented a broad range of ages from 18 to 84 years. Likewise, 30% of respondents reported more than 10 years of experience raising small ruminants, indicating that the survey included producers with a wide range of production experience rather than a single dominant experience level. Most respondents identified as White/Caucasian (95%) and non-Hispanic (95%). Sheep-only and goat-only operations represented similar proportions of respondents (43% and 42%, respectively), while 15%

reported raising both species. Production purpose was assessed using a multiple-response question; therefore, percentages were not mutually exclusive. Meat production was the most frequently selected enterprise (151/182; 83%), followed by dairy (40/182; 22%) and fiber (16/182; 9%). Herd size also varied among respondents, with the largest proportion (98/182; 54%) reporting ownership of 21 or more sheep or goats, while 8% (15/182), 14% (25/182), and 24% (44/182) reported herd sizes of 1–5, 6–10, and 11–20 animals, respectively.

Table 3:DESCRIPTIVE STATISTICS FOR PRODUCER INTEREST IN FORAGE-RELATED EDUCATIONAL TOPICS

Educational Topic	n	Mean	SD	Median	Selected 4 or 5 (%)
Extending the Grazing Season	182	4.47	0.82	5 (4-5)	86.7
Hay/Forage Quality	182	4.32	0.90	5 (4-5)	82.9
Forage-related Health Problems	182	4.28	0.97	5 (4-5)	80.6
Pasture Assessment	182	4.24	0.94	4 (4-5)	82.9
Rotational Grazing	182	3.99	1.12	4 (3-5)	70.2
Stocking Density	182	3.68	1.23	4 (3-5)	54.3
Mixed Species Grazing	182	3.61	1.46	4 (2-5)	58.5
Soil Testing	182	3.56	1.18	4 (3-5)	54.3
Poisonous Plants	182	3.55	1.27	4 (3-5)	51.9
Forage Testing	182	3.54	1.17	4 (3-4)	51.9
Weed Control	182	3.30	1.36	3 (2-5)	46.8

The analytic sample included 182 eligible Tennessee respondents; *n* represents the number of respondents who provided a valid rating for each educational topic and may vary because of item-level missing responses. SD = standard deviation; IQR = interquartile range. Educational interest was rated using a five-point Likert-type scale, where 1 = least interested and 5 = most interested. “Selected 4 or 5 (%)” represents the percentage of respondents who rated the topic as either 4 or 5.

Participants were asked to rate their level of interest in each of the 11 forage-related educational topics using a five-point Likert scale. Mean rating scores for all topics are presented in Table 3 and illustrated in Figure 2. Extending the grazing season received the highest mean rating (4.47), followed by hay and forage quality (4.32) and forage-related health problems (4.28). These three topics represented the highest educational priorities identified by Tennessee small-ruminant producers. Although the remaining topics received lower mean ratings, all topics averaged above the midpoint of the five-point scale, indicating continued producer interest across a broad range of forage management practices.

An optional open-ended question allowed respondents to identify additional educational topics not included in the structured survey. Relatively few respondents provided comments, and most responses addressed topics outside the scope of forage-related educational needs. Because these responses were not systematically coded or analyzed using qualitative methods, they are not presented in detail. However, the comments were shared with the University of Tennessee Small Ruminant Extension Specialist for consideration during future program planning.

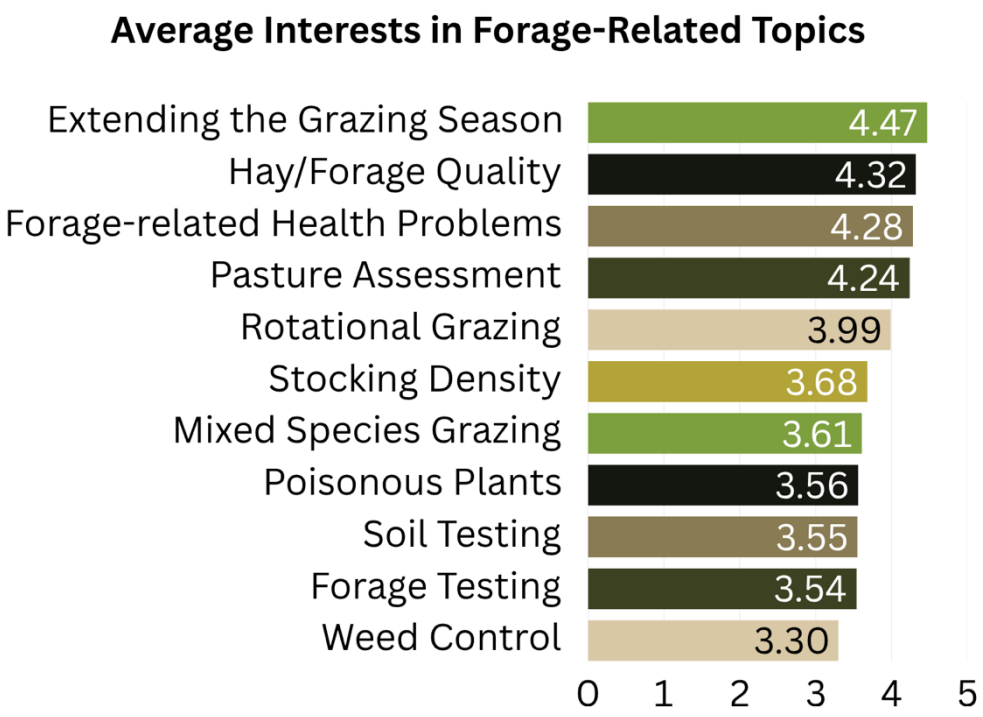

Figure 2:Figure 2: AVERAGE INTEREST IN FORAGE-RELATED TOPICS ON A LIKERT SCALE

Mean scores were obtained using a 1-5 scale with 1= the least interest and 5= most interested.

Discussion

Identifying forage-related educational needs among Tennessee small-ruminant producers is critical to ensuring that Extension programming is producer-driven and responsive to the needs of the industry. Previous research has demonstrated that conducting needs assessments before developing educational programming improves the relevance of Extension resources by prioritizing topics identified by producers rather than those perceived by educators (Al-Mazroa Smith & Miller, 2024). During the present

assessment, responses were received from producers representing 68 counties across Tennessee, with most respondents identifying as experienced producers. The three primary educational priorities that emerged were extending the grazing season, hay and forage quality, and forage-related health problems. These findings provide valuable direction for future University of Tennessee Extension programming while reinforcing the importance of regularly assessing producer educational needs.

The nationwide increase in feed costs has emphasized the economic importance of forage management and efficient grazing systems. Forage management remains one of the most influential factors affecting livestock production costs, requiring producers to understand how forage systems contribute to both animal performance and overall farm profitability (Ball et al., 2015). While Tennessee producers have access to both cool- and warm-season forage species that can be integrated to extend grazing opportunities, successful implementation requires an understanding of environmental conditions, forage growth, harvest management, and grazing strategies. Similar to Al-Mazroa Smith and Miller (2024), engaging producers in identifying their educational priorities allows Extension to develop programming that directly addresses producer concerns. Consequently, extending the grazing season, hay and forage quality, and forage-related health problems should remain priorities for future educational resource development.

Producer demographics provide important context for interpreting the educational priorities identified in this assessment. The largest proportion of respondents (27%) were between 45 and 54 years of age, while 30% reported more than ten years of experience raising small ruminants. These findings indicate that the survey captured producers

representing a range of ages and production experience, with the largest respondent groups consisting of middle-aged and relatively experienced producers. Similarly, the national needs assessment conducted by Whaley et al. (2022) included producers with diverse production backgrounds and identified educational priorities spanning multiple aspects of sheep and goat management. Collectively, these findings suggest that Tennessee Extension programming should continue to provide educational opportunities that address both foundational production practices and more advanced forage management topics to meet the needs of producers with varying levels of experience. Although the present survey did not evaluate preferred methods of educational delivery, previous Extension education research has demonstrated that offering educational programming through multiple delivery formats can improve accessibility and better address the diverse information-seeking behaviors of agricultural audiences (Franz et al., 2010; Kopiyawattage et al., 2018). Therefore, future programming for Tennessee small-ruminant producers, should incorporate a combination of in-person workshops, field demonstrations, webinars, and digital educational resources.

Women represented 52% of survey respondents, reflecting the increasing role of women in agricultural production and farm management observed nationally. According to the 2022 Census of Agriculture, women continue to represent a growing proportion of agricultural producers across the United States (USDA NASS, 2024). As the demographics of agricultural producers continue to evolve, Extension programming should remain inclusive and responsive to diverse audiences while recognizing differences in production goals, educational experiences, and preferred learning methods.

Extending the grazing season was identified as the highest-rated educational priority (4.47). This finding is consistent with the economic importance of grazing management, as extending grazing through practices such as rotational grazing, stockpiling, and the strategic use of cool- and warm-season forages can substantially reduce reliance on harvested feeds and lower production costs (Ball et al., 2015). Although Whaley et al. (2022) identified parasite management, breeding stock nutrition, and reproductive management as the highest educational priorities among producers nationwide, both studies demonstrate that producers prioritize management practices that directly influence profitability and operational efficiency. The strong interest in extending the grazing season among Tennessee producers likely reflects the importance of forage-based livestock production systems throughout the southeastern United States and the continued need to reduce feed costs through improved pasture management.

Hay and forage quality was identified as the second-highest educational priority (4.32). Forage quality directly influences nutrient intake, digestibility, animal performance, and overall productivity, making forage evaluation a critical management practice for livestock producers (Collins et al., 2007). Educational programming emphasizing forage testing, harvest timing, storage practices, and nutritional management can help producers make informed feeding decisions while maximizing forage utilization. The high ranking of this topic demonstrates producer recognition that improving forage quality contributes not only to animal performance but also to the economic sustainability of their operations.

Forage-related health problems ranked as the third-highest educational priority (4.28), highlighting the close relationship between forage management and animal health. Producer interest in topics such as nitrate toxicity, poisonous plants, bloat, and mineral deficiencies demonstrates the need for educational resources that integrate pasture management with livestock health. Although Whaley et al. (2022) reported parasite management as one of the highest national educational priorities, both studies indicate that producers value educational programming focused on preventing health-related production losses. Integrating forage management with animal health education may improve producer decision-making while supporting both animal welfare and production efficiency.

Overall, the findings of this study reinforce the importance of producer-driven needs assessments for guiding Extension programming. Similar to previous Extension needs assessments (Al-Mazroa Smith & Miller, 2024; Whaley et al., 2022), the educational priorities identified by Tennessee producers reflect management practices that directly influence profitability, sustainability, and animal performance. By using producer feedback to guide educational programming, the University of Tennessee Extension system can develop timely, relevant, and practical resources that address current forage management challenges while supporting the long-term sustainability of Tennessee's small-ruminant industry.

Limitations

While the findings from this needs assessment provide valuable guidance for future University of Tennessee Extension programming, several limitations should be

considered when interpreting the results. First, because participation in the survey was voluntary, the study is subject to potential selection bias. Producers with a greater interest in forage management or those already engaged with Extension programming may have been more likely to participate than producers with less interest in forage-related educational topics. Consequently, the educational priorities identified may overrepresent the interests of producers who actively seek educational resources. Additionally, the study is subject to response bias, as participants self-reported their educational interests and priorities. Responses reflect producers' perceptions of their educational needs at the time of the survey and may not necessarily represent their actual management practices or knowledge.

The survey was distributed exclusively through online recruitment methods, including social media and University of Tennessee Extension email distribution lists. Although this approach allowed the survey to reach producers across 68 Tennessee counties efficiently, it may have limited participation among producers with restricted internet access, lower levels of technology use, or limited engagement with Extension programming. As a result, the respondents represent a convenience sample rather than a random sample of Tennessee small-ruminant producers. Because the invitation was shared across multiple online platforms and could be redistributed by participants, a conventional response rate could not be calculated. The total number of producers who received or viewed the survey invitation was unknown; therefore, the proportion of eligible producers who participated could not be determined. Consequently, the findings may not fully represent the educational priorities of all Tennessee sheep and goat

producers. Despite these limitations, responses from 182 eligible producers representing 68 Tennessee counties provide valuable insight into current forage-related educational needs. These findings establish a strong foundation for developing producer-driven Extension programming while highlighting the importance of continued needs assessments to monitor changing educational priorities over time.

Conclusions

The month-long online needs assessment successfully identified the highest-ranked topics among respondents to this online sample, providing a producer-driven foundation for future University of Tennessee Extension programming. Responses from 182 eligible producers representing 68 Tennessee counties demonstrated strong interest in forage management education and highlighted the importance of developing educational resources that address the practical challenges faced by small-ruminant producers.

The findings indicate that extending the grazing season, hay and forage quality, and forage-related health problems are the highest educational priorities among respondents. These topics directly influence forage utilization, feed costs, animal performance, and the overall economic sustainability of sheep and goat operations. The demographic characteristics of respondents suggest that Extension programming should be designed to meet the needs of producers with diverse backgrounds and varying levels of production experience. Although many respondents reported more than ten years of experience raising small ruminants, the continued demand for advanced forage management education demonstrates that experienced producers continue to seek

management strategies that improve productivity, profitability, and long-term sustainability.

This assessment reinforces the importance of incorporating producer feedback into the planning and development of Extension programming. By identifying educational priorities directly from Tennessee sheep and goat producers, the University of Tennessee Master Small Ruminant Program can develop targeted educational resources that address current knowledge gaps while remaining responsive to the evolving needs of the industry. Because forage management plays a critical role in livestock productivity, feed costs, and overall farm sustainability, educational programming that reflects producer-identified priorities has the potential to improve management decision-making and encourage the adoption of best management practices.

By identifying forage-related educational priorities specific to Tennessee sheep and goat producers, this study addresses an important gap in the current Extension literature and provides a framework for developing evidence-based, producer-driven educational programming. Continued assessment of producer educational needs will help ensure that Extension resources remain relevant, practical, and responsive to changing production challenges, ultimately supporting the long-term sustainability and success of Tennessee's small-ruminant industry.

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CHAPTER FOUR

RECOMMENDATIONS

Implications

The findings of this thesis demonstrate the value of integrating applied research with producer-driven Extension programming to address forage management challenges within Tennessee's small-ruminant industry. Although the two studies addressed different objectives, they provide complementary information for guiding future research and educational programming. The in vitro digestibility experiment generated preliminary evidence describing the response of forage–DDG substrate mixtures under controlled laboratory conditions, whereas the statewide needs assessment identified forage-related topics that Tennessee sheep and goat producers consider priorities for future educational programming. Together, these studies establish a foundation for continued research while helping direct Extension efforts toward producer-identified needs.

The in vitro digestibility study demonstrated that 50:50 forage–DDG substrate mixtures exhibited greater measured in vitro true digestibility (IVTD) than forage-only substrates, regardless of forage nitrate concentration. However, these findings are limited to the total substrate evaluated within a controlled laboratory system and should not be interpreted as evidence that DDG improved the digestibility of the forage component, reduced nitrate toxicity, or enhanced animal performance. Furthermore, rumen inoculum was obtained from a single beef cow, and responses may differ among animals, diets, or ruminant species. Consequently, additional in vivo research is needed to determine whether similar responses occur under practical production conditions, to evaluate multiple DDG inclusion rates, and to investigate potential associative effects between DDG and high-nitrate forages before management recommendations can be developed.

The statewide needs assessment provides more immediate guidance for Extension programming by identifying forage-related educational priorities directly from Tennessee sheep and goat producers. Producer interest in extending the grazing season, hay and forage quality, forage-related health problems, and pasture assessment demonstrates a demand for science-based educational resources that strengthen forage management and decision-making. These findings support continued development of educational materials emphasizing established best management practices, including forage testing, pasture management, hay quality evaluation, and careful interpretation of forage nitrate analyses. Although the laboratory digestibility study contributes preliminary information for future investigation, recommendations regarding DDG supplementation with high-nitrate forages should await additional validation under in vivo conditions.

Collectively, these studies provide a framework for future integration of research and Extension programming within the University of Tennessee Master Small Ruminant Program. The producer needs assessment offers a clear roadmap for immediate educational efforts, while the digestibility experiment identifies questions requiring additional investigation before practical application. Future research should evaluate forage–DDG mixtures under commercial production conditions, quantify animal performance and nutrient utilization responses, investigate ruminal fermentation and nitrate metabolism, and determine practical supplementation rates across diverse forage systems. As additional evidence becomes available, those findings can be incorporated into Extension workshops, demonstrations, fact sheets, digital publications, and producer

training to ensure that educational recommendations remain evidence-based and applicable to Tennessee livestock operations.

More broadly, this thesis illustrates the importance of integrating scientific research with producer-driven needs assessments to guide future Extension programming. By combining laboratory-based research with direct producer input, this work establishes a process for identifying research priorities while ensuring that future educational programs remain responsive to the needs of Tennessee's sheep and goat producers. Continued collaboration among researchers, Extension specialists, and producers will strengthen the development of sustainable, evidence-based forage management strategies for small-ruminant production systems.

Future Work

Future research should continue building upon both the digestibility trial and the statewide needs assessment to strengthen the scientific foundation and practical application of forage management strategies for Tennessee small-ruminant producers. Together, these studies demonstrate the importance of integrating applied animal science research with producer-driven educational programming to address current and emerging challenges within the industry.

Future research should focus on validating these findings under conditions that more closely reflect practical livestock production systems while expanding the understanding of interactions between forage nitrate concentration and DDG supplementation. The present in vitro study demonstrated that 50:50 forage–DDG substrate mixtures exhibited greater in vitro true digestibility (IVTD) than forage-only

substrates, regardless of forage nitrate concentration. However, because IVTD was measured for the complete substrate rather than the forage fraction alone, additional research is needed to determine whether these responses represent associative effects between sorghum–sudangrass and DDG or simply reflect the greater digestibility of the combined substrate. Future in vivo studies should evaluate whether these responses translate to differences in animal performance, voluntary feed intake, nutrient utilization, nitrogen balance, and production efficiency under commercial management conditions. Additional research should investigate multiple DDG inclusion rates to identify practical supplementation strategies, while simultaneously evaluating nitrate metabolism, ruminal fermentation characteristics, and microbial nitrogen utilization in cattle consuming high-nitrate forages. Expanding this research to include additional warm-season annual forage species, different stages of forage maturity, and varying environmental conditions would improve understanding of how forage characteristics influence the response to DDG supplementation. Collectively, these studies would provide a stronger foundation for evaluating the practical application of DDG supplementation in forage-based production systems while further clarifying the biological mechanisms underlying responses observed during in vitro incubation.

The statewide needs assessment also identified several opportunities for continued research and Extension program development. Because producer educational needs and production challenges change over time, periodically repeating the assessment would allow the University of Tennessee Master Small Ruminant Program to monitor evolving educational priorities and emerging management concerns. Future surveys should

incorporate additional recruitment methods, including direct mail, producer organizations, livestock markets, and in-person Extension events, to improve participation among producers who may have limited access to online platforms or who are less engaged with social media. These strategies may improve the representativeness of future assessments while reducing potential sampling bias.

In addition to identifying producer priorities, future work should evaluate the effectiveness of Extension programming developed from these findings. Assessing changes in producer knowledge, management practice adoption, forage management decisions, and economic outcomes following participation in educational programs would provide valuable insight into the long-term impact of producer-driven Extension resources. Such evaluations would help determine whether educational programming successfully translates research findings into management practices that improve forage utilization, reduce feed costs, and enhance the sustainability of sheep and goat operations.

Collectively, future research should continue strengthening the connection between university research and Extension programming by combining scientific investigation with ongoing evaluation of producer educational needs. This integrated approach will support the development of evidence-based management recommendations and educational resources that remain responsive to changing industry needs while contributing to the long-term productivity, profitability, and resilience of Tennessee's small-ruminant industry.

APPENDIX

QUALTRICS SURVEY INSTRUMENT

THE UNIVERSITY of TENNESSEE

Forage Related Needs of TN Small Ruminant Producers

Survey Flow

Block: Demographics (11 Questions)
Standard: Block 1 (1 Question)
Standard: Block 2 (1 Question)

Page Break

THE UNIVERSITY of TENNESSEE

Q1 Are you a Tennessee Resident?

- No
- Yes

Q2 What County do you live in?

_____

_____

_____

_____

_____

Q3 Age

- Under 18
- 18 - 24
- 25 - 34
- 35 - 44
- 45 - 54
- 55 - 64
- 65 - 74
- 75 - 84
- 85 or older

Q4 Gender

- Male
- Female
- Non-binary / third gender
- Prefer not to say

Q5 Race

- Hispanic
- Non-Hispanic
- Prefer not to say

Q6 Ethnicity

- American Indian or Alaskan Native
- Asian/ Pacific Islander
- Black or African American
- Hispanic
- White/ Caucasian
- Other

Q7 Do you own sheep or goats?

- ○ Sheep
- ○ Goats
- ○ Both

Q8 Sheep/Goat Production Type (can select multiple)

- ☐ Meat
- ☐ Dairy
- ☐ Fiber

Q9 How many years have you raised small ruminants?

- ○ 0-3 years
- ○ 3-5 years
- ○ 6-10 years
- ○ 10+ years

Q10 Number of sheep or goats you own:

- ○ 1-5
- ○ 6-10
- ○ 11-20
- ○ 21+

Q11 Please list the breed(s) you raise.

_____

_____

_____

_____

_____

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Q10 Please rank each of the topics below from 1–5, with 1 being what you're least interested in learning about and 5 being what you're most interested in learning about

	Least Interested-1 (1)	2 (2)	3 (3)	4 (4)	Most Interested-5 (5)
Weed Control (1)	○	○	○	○	○
Poisonous Plants (2)	○	○	○	○	○
Hay/Forage Quality (3)	○	○	○	○	○
Forage Testing (4)	○	○	○	○	○
Soil Testing (5)	○	○	○	○	○
Rotational Grazing (6)	○	○	○	○	○
Stocking Density (7)	○	○	○	○	○
Extending the Grazing Season (8)	○	○	○	○	○
Pasture Assessment (9)	○	○	○	○	○
Mixed Species Grazing (10)	○	○	○	○	○
Forage Related Health Problems (11)	○	○	○	○	○

End of Block: Block 1

Start of Block: Block 2

THE UNIVERSITY of TENNESSEE

Q12 Are there any other forage related topics not listed that you would be interested in?

_____

_____

_____

_____

_____

End of Block: Block 2

VITA

Karlie Klingner obtained an associate from Dutchess Community College in Poughkeepsie New York before transferring to the University of Tennessee. At the University of Tennessee, she completed a bachelor's in animal science focusing in Bioscience during the summer of 2024. She then continued her education at UTK to pursue a master's degree in animal science under the mentorship of Dr. Katie Mason. Her committee members included Dr. Phil Myer and Dr. Bruno Pedreira, who all have contributed to the success of the project focusing on the digestibility of varying nitrate levels in sorghum-sudangrass and the inclusion of dried distillers' grains during an in vitro experiment. Klingner plans to continue her path in the agricultural industry, living each day to share her knowledge and passion to the following generations.