

REVIEW ARTICLE

***Tithonia diversifolia* as a multifunctional forage for ruminants: Nutritional value, fermentation, methane mitigation, and environmental sustainability**

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ABSTRACT

Tithonia diversifolia, commonly known as wild sunflower, is an underutilized tropical forage with considerable potential to support ruminant nutrition and environmentally sustainable livestock production, particularly in tropical and resource-limited regions. This review synthesizes current evidence on the nutritional characteristics, processing and fermentation technologies, effects on animal performance, methane mitigation potential, and environmental applications of *T. diversifolia*, while integrating these attributes within a climate-smart silvopastoral framework. Relevant literature was identified through searches of major scientific databases using combinations of keywords related to *T. diversifolia*, ruminant nutrition, fermentation, digestibility, animal performance, rumen fermentation, methane, soil, and sustainable livestock production, followed by screening of relevant studies. *T. diversifolia* generally contains relatively high crude protein content, commonly ranging from 20% to 25% of dry matter, together with nutritionally important minerals such as calcium and phosphorus. However, its utilization may be constrained by anti-nutritional compounds, including phytic acid, tannins, and oxalates, as well as variation associated with plant maturity, environmental conditions, and processing methods. Fermentation, particularly with lactic acid bacteria, offers a promising strategy for reducing selected anti-nutritional factors and improving nutrient availability, digestibility, preservation, and palatability. Animal feeding studies indicate that *T. diversifolia* can partially replace conventional feed resources and may support nutrient intake, digestibility, growth and milk production, although responses vary among animal species, inclusion levels, and experimental conditions. *In vitro* studies further indicate that its secondary metabolites, particularly tannins and saponins, can modify rumen fermentation and may reduce methane production under specific experimental conditions; however, evidence for consistent methane mitigation *in vivo* remains limited. Beyond its nutritional functions, its high biomass production, adaptability, and potential for nutrient recycling of *T. diversifolia* suggest possible applications in sustainable silvopastoral systems and soil management, although direct evidence for soil restoration and broader ecosystem services remains comparatively limited. The current evidence base is constrained by heterogeneity in plant material, nutritional composition, processing methods, inclusion levels, animal species, experimental designs, and outcome measurements, together with a limited number of long-term *in vivo* and field studies. Future research should prioritize optimization of fermentation technologies, long-term *in vivo* evaluation, elucidation of rumen microbiome and methane mitigation mechanisms, life cycle and economic assessments, and region-specific feeding strategies. Overall, *T. diversifolia* shows promise as a multifunctional tropical forage, but stringer and more standardized *in vivo* and field-based evidence is needed to establish its contributions to animal performance, methane mitigation, soil improvement, and broader ecosystem services.

Keywords: alternative forage, climate-smart livestock, enteric methane, fermentation, ruminant nutrition, silvopastoral

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systems, sustainable livestock, *Tithonia diversifolia*.

INTRODUCTION

The global livestock sector, particularly ruminant production, faces increasingly complex challenges arising from the growing demand for animal products, rising feed costs, climate-related constraints, and the need for more sustainable production practices. Feed resources are fundamental to livestock productivity; however, their availability and affordability are affected by economic, environmental, and supply-chain pressures worldwide. The increasing cost and fluctuating availability of conventional feed ingredients, together with seasonal variation in forage production, have encouraged the exploration of locally available alternative feed resources that can support animal productivity while reducing dependence on conventional feeds [1–5]. In addition, livestock production contributes substantially to global greenhouse gas (GHG) emissions, with feed production and processing, enteric fermentation and manure management representing major sources of livestock-related emissions [6].

Among these environmental concerns, enteric methane production is particularly relevant in ruminant systems because it contributes to global warming and also represents a loss of dietary energy, which may reach up to 12% of gross energy intake [7–9]. Consequently, alternative feed resources that simultaneously provide nutrients and contain bioactive compounds capable of modifying rumen fermentation have attracted increasing attention.

Tithonia diversifolia, commonly known as wild sunflower, is one such alternative forage resource. The plant contains secondary metabolites, including tannins and saponins, that may suppress rumen protozoal activity and contribute to reduced methane production [10]. It is also adaptable to relatively poor soil conditions and can reduce substantial biomass with limited external inputs, characteristics that support its potential as a locally available forage in resource-constrained production systems [11]. Previous studies have indicated that *T. diversifolia* can partially replace conventional feed ingredients while supporting nutrient utilization, growth, or milk production, although responses vary according to inclusion level, plant maturity, processing method, animal species, and experimental conditions [12–14]. The potential multifunctional *T. diversifolia* tropical livestock systems, encompassing its established nutritional functions and proposed environmental applications, is conceptually illustrated in Figure 1.

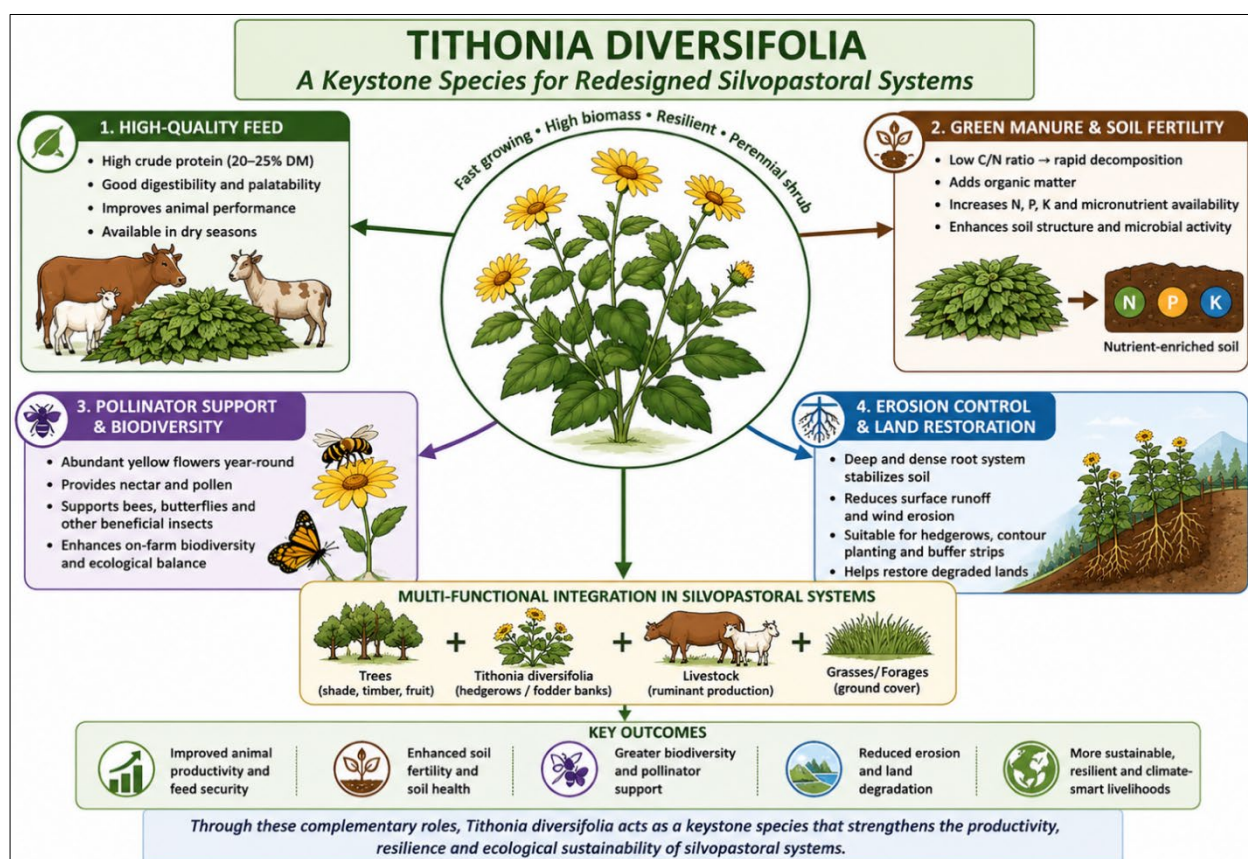


Figure 1: Conceptual multifunctional component for redesigned silvopastoral systems.

Despite growing interest in *T. diversifolia* as an alternative forage for ruminants, previous reviews have primarily addressed specific aspects of the plant, including nutritional composition, phytochemical characteristics, agronomic potential, or use as a feed resource. However, these reviews have not comprehensively integrated evidence on processing and fermentation technologies with nutrient utilization, animal performance, rumen fermentation, methane mitigation, and potential environmental applications. This fragmented coverage makes it difficult to assess the broader role of *T. diversifolia* across both animal production and environmental sustainability. Therefore, a comprehensive synthesis is needed to connect the nutritional and functional characteristics of *T. diversifolia* with evidence from processing and fermentation, ruminant feeding trials, rumen fermentation studies, and emerging environmental applications. Such an integrated perspective can help identify where evidence is well established, where findings remain inconsistent, and where further *in vivo*, field-based, and long-term research is required. This approach also provides a basis for evaluating the potential integration of *T. diversifolia* into sustainable and climate-smart tropical livestock systems without overstating the current evidence.

This review aimed to synthesize current knowledge on *T. diversifolia* as a multifunctional forage resource for ruminant production, with emphasis on its nutritional characteristics, anti-nutritional factors, processing and fermentation technologies, effects on nutrient utilization and animal performance. The review further examines evidence regarding rumen fermentation and methane related responses, as well as the potential environmental applications in sustainable and silvopastoral livestock systems. By integrating these dimensions, this review identifies areas where evidence is established or remains limited, highlights key knowledge gaps and proposes research priorities for the practical utilization of *T. diversifolia* within sustainable and climate-smart tropical ruminant production systems.

REVIEW METHODOLOGY

This review was conducted as a narrative literature review with a structured search approach to identify and synthesize published evidence on *T. diversifolia* as a multifunctional forage resource for ruminant production. The review focused on its nutritional composition, anti-nutritional factors, processing and fermentation technologies, nutrient utilization, animal performance, rumen fermentation, enteric methane mitigation, agronomic characteristics, environmental applications, and integration into sustainable and silvopastoral production systems.

A comprehensive literature search was conducted using Scopus, Web of Science, PubMed, ScienceDirect, and Google Scholar. The search covered publications from January 2000 to April 2026, while older seminal studies were considered when necessary to provide historical or conceptual context. Search terms were used individually and in combinations and included "*Tithonia diversifolia*," "Mexican sunflower," "wild sunflower," "ruminant," "cattle," "goat," "sheep," "forage," "nutritional composition," "crude protein," "digestibility," "anti-nutritional factors," "fermentation," "silage," "rumen fermentation," "methane," "greenhouse gas," "animal performance," "soil fertility," "nutrient cycling," "silvopastoral system," and "sustainable livestock." Boolean operators (AND and OR) were applied, where supported by the database, to combine terms and refine the searches.

Peer-reviewed original research articles and relevant review articles published in English were considered for inclusion when they provided information directly relevant to at least one of the predefined themes of this review. Studies involving *T. diversifolia* as a forage, feed ingredient, processed or fermented feed, soil amendment, or component of an integrated livestock production system were considered where their findings contributed to the nutritional, productive, environmental, or agronomic objectives of the review. Studies involving ruminants were prioritized for nutritional, digestibility, rumen fermentation, methane emission, and animal performance outcomes. Agronomic and environmental studies were included when they provided evidence relevant to biomass production, nutrient cycling, soil improvement, ecosystem services, or silvopastoral integration.

Publications were excluded when they were unrelated to *T. diversifolia*, did not address outcomes relevant to the scope of the review, lacked sufficient methodological or outcome information for meaningful interpretation, or consisted solely of non-scientific commentary. Duplicate records identified across databases were removed. Titles and abstracts were initially screened for relevance, followed by assessment of the full text of potentially eligible publications. Reference lists of relevant articles were also examined to identify additional studies that were not retrieved through the primary database searches.

Information from the included literature was organized thematically according to nutritional composition, protein and amino acid profile, fiber and energy characteristics, mineral and vitamin composition, anti-nutritional factors, processing and fermentation, nutrient digestibility, rumen fermentation, productive responses, methane

mitigation potential, agronomic characteristics, and environmental and silvopastoral applications. Because of substantial heterogeneity among studies in experimental design, animal species, dietary inclusion levels, processing methods, analytical procedures, environmental conditions, and reported outcomes, the evidence was synthesized narratively rather than by meta-analysis. Quantitative values reported in the review were retained in the units and contexts of the respective studies and were compared descriptively where appropriate.

IMPORTANCE OF ALTERNATIVE FEED SOURCES

The exploration of alternative feed resources is increasingly important in tropical and resource-limited regions because of the growing pressures of climate change, limited availability of arable land, rising feed costs, and the nutritional inadequacy of many conventional forage resources. These constraints necessitate sustainable feeding strategies capable of maintaining ruminant productivity, particularly during seasonal fluctuations in forage availability. Natural pastures and other traditional feed resources often fail to meet the nutritional requirements of ruminants during the dry season because both forage quantity and quality decline substantially [15]. Consequently, nutrient-dense, locally available, and cost-effective alternative feeds are increasingly needed to complement conventional resources. *T. diversifolia* is among the forage species with considerable potential as an alternative feed resource (Table 1) [14, 16, 17].

Table 1: Potential of *Tithonia diversifolia*.

Topic	Characteristics and potential	Reference
Nutritional content	CP = 22.98%–31.02%	[16, 17]
	DM = 25.57%–91.76%	[14]
	OM = 84.01%–88.40%	[14, 16]
	CF = 16.52%–18.84%	[14]
	Processing with <i>Lactobacillus plantarum</i> and <i>Aspergillus ficuum</i> improves digestibility and reduces anti-nutritional factors	[14]
Use in ruminant feed	Increases RDP and microbial protein synthesis	[17]
	Reduces methane production through the effects of secondary metabolites, including tannins and saponins	[17]
Application in feed formulation	Used in combination with <i>Leucaena leucocephala</i> to improve dietary protein balance and digestibility	[17]
	Fermentation enhances CP and phytase activity	[14]
	Fermentation for 7 days improves feed characteristics, including OM, and reduces undesirable components such as lignin	[16]
Digestibility	DMD = 64.56%–66.86%	[14]
	OMD = 63.89%–67.36%	[14, 17]
	CPD = 62.52%–70.37%	[14]
	CFD = 60.78%–81.01%	[14]

CF = crude fiber; CFD = crude fiber digestibility; CP = crude protein; CPD = crude protein digestibility; DM = dry matter; DMD = dry matter digestibility; OM = organic matter; OMD = organic matter digestibility; RDP = rumen-degradable protein.

Seasonal variation in natural pasture availability represents a major challenge because mature or dry season forages are frequently characterized by low protein and other essential nutrient concentrations and relatively high fiber contents, thereby limiting nutrient intake and animal productivity [18]. This nutritional imbalance emphasizes the importance of supplementary feed resources that can bridge nutrient deficits during periods of forage scarcity. Multipurpose trees and shrubs, including *Moringa oleifera* and *Erythrina edulis*, have demonstrated potential as supplementary feeds because of their relatively high protein and mineral contents. In addition to contributing nutrients to ruminant diets, these plants may provide environmental benefits through improvements in soil health and biodiversity [19]. Such locally available alternative protein sources are particularly relevant in the context of volatile feed prices and increasing competition between livestock feed production and crops intended for human consumption [20].

Agricultural by-products also represent potentially valuable alternative feed resources. Oilseed cakes, fruit-processing residues, and other agro-industrial by-products can provide substantial quantities of nutrients and are often less expensive than conventional feed ingredients [21]. In this context, *T. diversifolia*, commonly known as Mexican sunflower, has attracted considerable interest because of its protein and mineral contents, widespread occurrence in tropical regions, and adaptability to diverse environmental conditions. Its nutritional composition is comparable to that of some leguminous forages, with CP concentrations reported to reach approximately 22%–

23% of dry matter (DM) [14]. In addition, *T. diversifolia* can produce up to 10 tons of DM/ha annually, demonstrating its considerable potential for biomass production [22].

An additional advantage of *T. diversifolia* is its adaptability to relatively unfavorable environmental conditions. The plant can grow in degraded and acidic soils with relatively low fertilizer and water requirements, characteristics that may facilitate forage production in areas constrained by limited arable land and agricultural inputs [23]. Its adaptability to acidic soils and drought conditions further supports its potential use in climate-stressed production environments. Moreover, *T. diversifolia* may contribute to soil fertility by mobilizing phosphorus and supplying organic matter (OM) during biomass decomposition, thereby improving nutrient cycling and potentially reducing dependence on synthetic fertilizers [24].

The incorporation of legumes and other locally available feed resources into ruminant diets may similarly improve nutrient intake and animal performance [25]. For example, fodder radish has been investigated as an alternative forage capable of supporting nutrient supply and digestibility during periods of feed scarcity [26]. Leguminous forage species can provide additional agronomic benefits through biological nitrogen fixation, which contributes to soil fertility and biomass production while supporting sustainable forage systems [27]. Thus, incorporating locally available alternative feeds into ruminant diets can address immediate nutritional requirements while strengthening the long-term resilience of livestock production systems by reducing dependence on scarce and costly conventional feed resources [7, 28].

The utilization of agricultural by-products in combination with *T. diversifolia* provides another opportunity for developing cost-effective feeding strategies. Studies conducted in Indonesia have demonstrated that diets combining *T. diversifolia* with agricultural by-products, including fermented sugarcane-based feeds, can support feed intake, nutrient digestibility, and productive performance in goats [29]. In such combinations, fermented sugarcane-derived feed can provide an energy source, whereas *T. diversifolia* contributes dietary protein. This complementary nutritional approach may reduce dependence on expensive concentrate ingredients and provide a practical feeding strategy for smallholder livestock systems. The use of locally available resources may also strengthen circular agricultural systems by converting agricultural residues into nutritionally useful livestock feeds.

Beyond their nutritional value, some alternative feeds contain bioactive compounds capable of modifying rumen fermentation. *T. diversifolia* contains tannins and saponins, which have been associated with changes in rumen protozoal activity and reduced methane production [30]. These properties increase interest in the plant as a feed resource that may simultaneously contribute to animal nutrition and environmental sustainability. Certain alternative feed resources have also been investigated for antimicrobial properties [31]. However, the potential health benefits of such compounds should be distinguished from demonstrated therapeutic efficacy in ruminants, and their practical relevance requires appropriate evaluation under controlled feeding conditions.

Collectively, alternative feed resources offer a multifaceted strategy for addressing forage scarcity, high feed costs, nutritional limitations, and the environmental impacts of livestock production in tropical and resource-constrained regions. Greater utilization of locally available forage species, multipurpose plants, legumes, and agricultural by-products can diversify feed supplies and reduce dependence on conventional ingredients. Such diversification may simultaneously support livestock productivity, resource-use efficiency, smallholder resilience, and environmentally sustainable production systems.

Compared with other tropical forage species, including *Moringa oleifera*, *Leucaena leucocephala*, and *Gliricidia sepium*, *T. diversifolia* combines several nutritional, agronomic, and environmental attributes (Table 2) [32-46]. In addition to its relatively high CP concentration and biomass production, *T. diversifolia* can grow under relatively low-input conditions, while its secondary metabolites, particularly tannins and saponins, have been associated with altered nitrogen utilization and enteric methane production. Furthermore, its potential contribution to phosphorus mobilization and OM recycling extends its relevance beyond animal nutrition to soil fertility and nutrient cycling. These combined characteristics support consideration of *T. diversifolia* as a multifunctional forage resource rather than solely as an alternative source of dietary protein.

Based on these characteristics, a conceptual Tithonia opportunity framework (TIF) is proposed to organize the multidimensional potential of *T. diversifolia* as a multifunctional forage across six dimensions: nutrient density, anti-nutritional factor manageability, methane mitigation potential, soil and ecosystem benefits, farmer accessibility, and climate resilience. The framework is intended as a qualitative conceptual synthesis of the attributes and evidence discussed in this review and does not constitute a quantitative index, scoring system,

ranking, or validated assessment tool. It provides a structured basis for considering the nutritional, environmental, agronomic, and practical dimensions of *T. diversifolia* simultaneously, while highlighting areas where further empirical validation is needed before broader application in sustainable tropical livestock production.

OVERVIEW OF *T. diversifolia*

T. diversifolia, commonly known as Mexican sunflower or wild sunflower, is a versatile and resilient shrub belonging to the family Asteraceae. Native to Central America, it is now widely distributed throughout tropical and subtropical regions, including parts of Africa and Asia [47]. The plant can grow up to 3 m in height and produces distinctive yellow flowers that may bloom throughout the year under favorable environmental conditions [48]. Its broad environmental adaptability and ability to establish under diverse climatic conditions have increased interest in its use as a forage resource, particularly in resource-limited production systems where conventional feeds may be scarce or nutritionally inadequate. Genetic variation and genotype × environment interactions involving factors such as soil fertility and climatic conditions contribute to differences in biomass production, nutrient composition, and adaptation, indicating opportunities for selecting superior genotypes suited to different production environments [49]. Despite these advantages, *T. diversifolia* is considered invasive in some tropical regions because of its rapid growth and seed dispersal; therefore, appropriate cultivation and containment practices are necessary to minimize potential ecological risks [12].

Table 2: Qualitative comparison of *Tithonia diversifolia* with selected tropical forage species based on published evidence.

Evaluation criteria	<i>Tithonia diversifolia</i>	<i>Moringa oleifera</i>	<i>Leucaena leucocephala</i>	<i>Gliricidia sepium</i>	Reference
Nutrient density	Reported as a protein-rich tropical forage with potential for use in ruminant diets	Nutritionally valuable foliage with reported protein and mineral content	Protein-rich forage with high nutritional value	Protein-rich forage with potential for ruminant feeding	[32–35]
Anti-nutritional factor management	Contains tannins and other secondary compounds; effects depend on concentration, diet and animal response	Generally reported to contain relatively low levels of some anti-nutritional factors, although composition varies	Contains mimosine and other secondary compounds requiring appropriate management	Contains secondary compounds that may influence nutrient utilization depending on concentration	[36–38]
Methane mitigation potential	Reported potential associated with secondary metabolites, particularly tannin, although evidence is context-dependent	Secondary metabolites may influence rumen fermentation and methane information	Tannin and other secondary compounds may contribute to methane mitigation	Reported potential effects on rumen fermentation and methane formation	[39–41]
Soil and ecosystem benefits	Reported applications in biomass production, nutrient cycling, green manuring, and soil fertility improvement	Reported agroforestry and soil-related applications	Used in agroforestry and soil fertility management systems	Used in agroforestry and soil improvement systems	[42–44]
Farmer accessibility	Potentially accessible in tropical production systems because of its biomass production and adaptability although local availability varies	Availability and adoption depend on production system and location	Widely used in some tropical livestock systems, with management requirements	Used as a fodder tree in tropical smallholder systems, with regional variation	[35, 45]
Climate resilience	Reported adaptability across tropical environment, although performance depends on site and management conditions	Adaptation varies with environmental conditions and production systems	adapted to various tropical environment, with performance depends in site conditions	Adapted to tropical production systems, with regional variation	[42, 45, 46]

Table 2 provides a descriptive synthesis of published evidence across the selected forage species. The comparisons are intended to provide contextual information rather than quantitative rankings, as differences in study design, plant maturity, growing conditions, processing, diet formulation, and evaluation methods limit direct cross-study comparisons.

As a forage resource, *T. diversifolia* is notable for its nutritional value, particularly its relatively high protein content, which can reach approximately 22.89% of DM, supporting its potential use as a protein supplement in ruminant diets [14]. Its biomass also contains nutritionally important elements, including nitrogen, phosphorus, and potassium [50]. In addition to its nutrient composition, *T. diversifolia* contains bioactive secondary metabolites, particularly tannins and saponins, which can modify rumen fermentation and have been associated

with reduced methane production in ruminants [17]. These characteristics have generated interest in *T. diversifolia* not only as an alternative forage but also as a potential component of feeding strategies designed to improve the environmental sustainability of ruminant production.

Despite its nutritional advantages, the utilization of *T. diversifolia* may be constrained by anti-nutritional factors, including phytic acid, tannins, and oxalates [14, 23]. At elevated concentrations, these compounds may interfere with nutrient utilization and potentially reduce palatability and digestibility, thereby limiting animal performance. Various processing approaches have therefore been investigated to improve the feeding value of *T. diversifolia*. Fermentation with *Lactobacillus bulgaricus*, for example, has been reported to reduce phytic acid concentrations and improve the availability of minerals and proteins [14]. Appropriate processing and fermentation may therefore help mitigate some of the nutritional limitations associated with anti-nutritional factors and improve the suitability of *T. diversifolia* as a ruminant feed ingredient.

The widespread distribution of *T. diversifolia* is partly attributable to its capacity to establish in diverse environments, including roadsides, disturbed areas, and agricultural land [51]. It can grow in relatively poor soils, including acidic and nutrient-deficient soils, and has the capacity to acquire and mobilize phosphorus, an important characteristic in tropical soils where phosphorus availability may be limited [52]. Furthermore, the relatively low carbon-to-nitrogen (C/N) ratio of *T. diversifolia* biomass facilitates rapid decomposition when incorporated into soil as green manure, thereby promoting nutrient release and potentially improving crop productivity [53]. Its rapid growth, vigorous regrowth following harvesting, and adaptability to low-fertility soils also make it suitable for repeated harvesting as a forage crop [23, 24].

Appropriate management is essential to balance the productive benefits of *T. diversifolia* with its potential invasiveness. Practices such as regular harvesting before seed set, controlled cultivation, and monitoring of plant spread can help reduce ecological risks while allowing its utilization as a forage resource. Beyond animal nutrition, *T. diversifolia* has potential applications in soil fertility management. Incorporation of its biomass into soil has been associated with increased phosphorus availability, which may be particularly beneficial in degraded tropical soils [54]. Consequently, its use as green manure provides an opportunity to integrate forage production with nutrient recycling and soil fertility improvement. Such integration may reduce dependence on external fertilizer inputs while contributing to soil-conservation and biodiversity within diversified agricultural systems [55].

Mexican sunflower also has considerable biomass production potential. Under favorable conditions and repeated harvesting, *T. diversifolia* can produce approximately 4.1–10.2 tons of DM/ha annually, providing a potentially abundant forage resource during periods when conventional forage availability and quality decline [22]. Biomass production varies according to harvest frequency, soil fertility, climatic conditions, and genetic characteristics [22, 24, 49]. The combination of substantial biomass production and favorable nutrient composition makes *T. diversifolia* a potentially useful supplementary forage in regions where conventional forage production is constrained. Dietary studies have indicated that *T. diversifolia* can replace up to 35% of conventional concentrates in dairy cattle diets without adversely affecting milk production or quality [56].

The inclusion of *T. diversifolia* in ruminant diets has also been evaluated for its effects on animal productivity. Studies in dairy cattle indicate that dietary inclusion of *T. diversifolia* can support milk production when used as a supplementary feed [57]. In goats and other small ruminants, feeding trials have reported improvements in nutrient digestibility and body weight gain following the inclusion of *T. diversifolia*, supporting its potential application across different ruminant production systems [58]. Its relatively high CP content and digestibility may be particularly valuable for animals with high dietary protein requirements, including lactating dairy cows and goats [51].

Beyond its direct role as forage, *T. diversifolia* has the potential to function as a multifunctional component of sustainable silvopastoral systems. Its combined capacity to provide nutrient-rich biomass, contribute OM and nutrients to soils, support pollinators, and contribute to erosion control provides a basis for integrating forage production with broader ecosystem functions. These characteristics may enhance the resilience and multifunctionality of livestock production systems, particularly where feed scarcity, declining soil fertility, and climatic variability occur simultaneously.

Overall, *T. diversifolia* is an adaptable alternative forage with potential applications extending from ruminant nutrition to soil fertility management and environmental sustainability. Its capacity to produce nutritionally valuable biomass under relatively challenging growing conditions, together with its potential contributions to nutrient cycling and ecosystem functions, supports its use in tropical and subtropical livestock systems. However,

its practical value depends on appropriate dietary inclusion, management of anti-nutritional factors, locally adapted cultivation and harvesting practices, and measures to control unintended plant spread. Accordingly, *T. diversifolia* should be considered a potentially multifunctional forage resource whose nutritional, agronomic, and environmental benefits need to be balanced against management requirements and ecological risks [51].

PROTEIN CONTENT AND AMINO ACID PROFILE

T. diversifolia has attracted considerable attention as a protein-rich forage with the potential to support ruminant nutrition in regions where conventional protein sources are limited or expensive. Its CP content ranges from approximately 26.04% to 35.59%, which is relatively high compared with that of many conventional forage grasses and some legumes [9]. Dietary protein is essential for supporting tissue growth, enzyme and hormone synthesis, and productive functions in ruminants. However, CP concentration alone does not fully characterize the nutritional value of a forage; its amino acid composition, ruminal protein degradability, and post-ruminal protein supply are also important determinants of feeding value. *T. diversifolia* contains essential amino acids that contribute to its potential as an alternative protein source for ruminants [51].

In ruminant nutrition, dietary protein is commonly characterized according to its ruminal degradability as rumen-degradable protein (RDP) and rumen-undegradable protein (RUP). An appropriate balance between RDP and RUP is important for efficient protein utilization. RDP is degraded by rumen microorganisms, providing nitrogenous substrates for microbial growth and microbial protein synthesis, whereas RUP escapes ruminal degradation and can contribute directly to the metabolizable protein supply after intestinal digestion. The relatively high CP content of *T. diversifolia* may provide an important source of RDP, thereby supporting microbial protein synthesis and nitrogen utilization [59, 60]. The nutritional composition reported for *T. diversifolia* in different studies is summarized in Table 3 [61–65]. Considerable variation among reported values may be associated with harvest maturity, genotype, environmental conditions, soil fertility, and post-harvest processing methods, including drying and fermentation. Younger plants generally contain more CP and less structural carbohydrate, whereas advancing maturity is associated with increased fiber fractions and reduced nutrient digestibility. These factors should therefore be considered when interpreting compositional data and determining the appropriate use of *T. diversifolia* in ruminant feeding systems.

Table 3: Amino acid, vitamin, mineral, and energy composition of *Tithonia diversifolia*.

Component	Content	Reference
Amino acids (g/kg CP)	Aspartic acid (29.98), glycine (26.44), valine (24.11), lysine (21.30), proline (21.21), glutamic acid (21.06), leucine (20.67), serine (19.55), alanine (19.12), phenylalanine (13.32), threonine (12.96), methionine + cystine (11.72), arginine (9.15), isoleucine (8.26), methionine (6.60), cystine (5.12), and histidine (3.33)	[61]
Vitamins (%)	Total carotenoids (0.92), trans-lutein (50.67), carotene esters (30.49), β -cryptoxanthin (6.40), epoxy-trans-lutein (1.95), and trans-zeaxanthin (0.65)	[62]
Minerals (g/kg DM)	Potassium (39.61), calcium (32.41), phosphorus (7.20), magnesium (4.68), iron (0.26), zinc (0.11), manganese (0.06), and copper (0.003)	[63]
Energy content	Gross energy = approximately 15.4–15.7 MJ/kg DM; digestible energy = approximately 12.4 MJ/kg DM; metabolizable energy = approximately 9.9 MJ/kg DM or 2565–2908 kcal/kg DM, depending on harvest age, cultivation location, and energy estimation method	[64, 65]

CP = crude protein; DM = dry matter; MJ = megajoule.

The amino acid profile of *T. diversifolia* includes essential amino acids such as lysine and methionine, which are relevant to tissue protein synthesis, immune function, and milk protein synthesis [51]; however, their effective post-ruminal supply depends on the extent of ruminal degradation, microbial protein synthesis, and subsequent intestinal digestibility. These amino acids may be limiting in some tropical forage-based diets; therefore, the amino acid contribution of *T. diversifolia* may complement diets in which conventional protein sources are insufficient [57]. Compared with several tropical forages, including *Gliricidia sepium* and *Stylosanthes guianensis*, *T. diversifolia* has been reported to provide comparable or higher CP concentrations while maintaining favorable nutritional characteristics during the dry season [24, 45].

The relatively high protein concentration of *T. diversifolia* also supports its potential use as a partial replacement for commercial concentrates, which may reduce dependence on costly conventional protein sources [66]. Feeding studies involving Pesisir cattle and goats have reported favorable responses in nutrient intake, digestibility, body weight gain, and milk production following dietary inclusion of *T. diversifolia* [14, 42, 58].

Nevertheless, the plant contains anti-nutritional compounds, including phytic acid, that may limit nutrient utilization. Biological processing methods such as fermentation can reduce some of these compounds and improve nutrient bioavailability and feeding value [29]. The effects of these processing strategies are discussed in detail in subsequent sections.

FIBER, CARBOHYDRATE, AND ENERGY CONTENT

The fiber, carbohydrate, and energy characteristics of *T. diversifolia* are important determinants of its suitability as a forage resource for ruminants, particularly under tropical production conditions. Its structural carbohydrate profile influences voluntary intake, ruminal fermentation, digestibility, and energy availability. The plant has been reported to contain relatively moderate fiber concentrations compared with many mature tropical forages, which may contribute to its favorable digestibility and potential use as a component of nutritionally balanced ruminant diets.

The crude fiber content of *T. diversifolia* has been reported to average approximately 11.2% in some conventional forage resources [67]. However, crude fiber values should be interpreted cautiously because they may according to plant maturity, plant fraction, growing conditions, and analytical procedures. Excessive dietary fiber, particularly poorly digestible structural material, can constrain voluntary intake and nutrient utilization. However, crude fiber is a relatively limited analytical measure of forage cell wall composition; therefore, neutral detergent fiber (NDF), acid detergent fiber (ADF), and lignin concentrations provide additional information for evaluating the feeding value of *T. diversifolia*.

The NDF content of *T. diversifolia* has been reported at approximately 45.4% [67]. NDF represents major plant cell wall constituents, including hemicellulose, cellulose, and lignin, and is closely associated with rumen fill, voluntary feed intake, and forage digestibility. Increasing NDF concentration is generally associated with reduced potential intake and digestibility, although the response depends on fiber digestibility and other dietary characteristics. The reported NDF concentration provides an indication of the structural carbohydrate fraction of *T. diversifolia*; however, its effects on intake and digestibility depend on fiber digestibility, plant maturity, inclusion level and the composition of the complete diet. Favorable nutrient intake and productive responses have also been reported when the plant was incorporated into diets for dairy goats [66].

The energy value of *T. diversifolia* should be distinguished among cross gross energy (GE), digestible energy (DE), and metabolizable energy (ME), as these measures represent different stages of energy availability to the animal. GE reflects the energy contained in the feed, whereas DE and ME account progressively for energy losses associated with fecal and urinary, gaseous, and other metabolic processes. Therefore, contribution of *T. diversifolia* to dietary energy depends on its nutrient composition, digestibility, fermentation, inclusion level, and the composition of the complete ration. Available feeding studies have indicated that *T. diversifolia* can contribute to nutritionally balanced diets when appropriately combined with complementary feed resources [9].

Lignin concentration is another important determinant of forage digestibility because lignification restricts microbial access to cellulose and hemicellulose within the plant cell wall. Consequently, lower lignification can increase the proportion of structural carbohydrates available for microbial fermentation. Feeding studies involving *T. diversifolia* have reported favorable nutrient digestibility and voluntary feed intake relative to diets containing more highly lignified forage resources [30]. Nevertheless, these responses should be interpreted within the context of the experimental diet and should not be directly compared across studies with different forage characteristics, inclusion levels, or analytical methods.

Ruminal fermentation of digestible carbohydrates produces volatile fatty acids (VFAs), primarily acetate, propionate, and butyrate, which constitute major energy sources for ruminants. Acetate is particularly important as a precursor for milk fat synthesis, whereas propionate contributes substantially to hepatic glucose production. Dietary inclusion of *T. diversifolia* has been associated with changes in ruminal fermentation and VFA production [30]. These changes may reflect differences in carbohydrate availability and fermentation patterns associated with the inclusion of *T. diversifolia*. Fermentation patterns are also influenced by the entire dietary matrix rather than by a single forage component.

The carbohydrate profile of *T. diversifolia* may also support rumen microbial activity by supplying fermentable substrates. Adequate synchronization between fermentable energy and rumen-available nitrogen is important for microbial growth and microbial protein synthesis. Studies using mixed diets have indicated that inclusion of *T. diversifolia* can influence overall diet digestibility [67]. Microbial protein synthesized in the rumen

subsequently contributes to the metabolizable protein supply after digestion and absorption in the small intestine.

In practical feeding systems, *T. diversifolia* has been evaluated as a partial replacement for conventional forage and concentrate ingredients. Feeding trials involving Pesisir cattle and dairy goats have demonstrated favorable responses in nutrient intake and digestibility when *T. diversifolia* was incorporated at appropriate dietary levels [68]. Its inclusion should nevertheless be balanced with other forage and concentrate ingredients to provide adequate energy, protein, effective fiber, minerals, and other nutrients required for rumen function and animal production.

The nutritional characteristics of *T. diversifolia* vary with plant maturity and processing. As the plant matures, fiber fractions, particularly ADF and lignin may increase, whereas nutrient digestibility may decline depending on growing conditions and plant characteristics. Changes in energy value should likewise be interpreted cautiously because reported gross, digestible, and ME values are influenced by diet composition, analytical methods, and the approach used for energy estimation. Conversely, microbial fermentation has been reported to modify structural fiber fractions, improve nutrient availability, and enhance digestibility through partial degradation of plant cell wall components [14, 29, 58]. Although recent studies have reported fiber fractions and estimated energy values, comprehensive assessments integrating metabolizable energy, total digestible nutrients, VFA production, and *in vivo* or *in sacco* digestibility kinetics remain limited and warrant further investigation.

Beyond nutrient concentration, the practical feeding value of *T. diversifolia* is strongly influenced by nutrient bioavailability and digestibility [17, 60]. Fermentation has been reported to improve protein accessibility, modify fiber fractions, reduce selected anti-nutritional compounds, and enhance nutrient digestibility [9, 14, 23, 58]. Therefore, future evaluations should integrate conventional chemical composition with post-processing nutrient availability and digestibility to provide a more comprehensive assessment of the feeding value of *T. diversifolia* for ruminants.

MINERAL AND CAROTENOIDS COMPOSITION

T. diversifolia is recognized not only for its relatively high protein content but also for its mineral composition, which may contribute to meeting the nutritional requirements of ruminants. Its mineral profile includes calcium, phosphorus, potassium, and magnesium, which are involved in physiological processes such as skeletal development, muscle function, electrolyte balance, and energy metabolism [69]. The plant also contains carotenoids with provitamin A activity; however, information on its broader vitamin composition remains comparatively limited [70].

The mineral composition of *T. diversifolia* varies considerably among studies because of differences in soil fertility, environmental conditions, plant maturity, genotype, and post-harvest processing. Despite this variability, relatively high concentrations of calcium, potassium, phosphorus, and magnesium have been reported, indicating that the forage can contribute to the mineral supply of ruminants when incorporated into appropriately balanced diets [61, 63]. Nevertheless, mineral concentrations should be considered in relation to total dietary supply, bioavailability, animal requirements, and mineral interactions. In particular, an appropriate calcium-to-phosphorus ratio is important for maintaining efficient mineral utilization and animal health.

Calcium is essential for skeletal development, muscle contraction, blood coagulation, and several cellular processes. Its importance increases during lactation because of the substantial calcium requirement associated with milk synthesis. Although the calcium concentration of *T. diversifolia* varies according to growing and harvesting conditions, feeding studies indicate that the plant can contribute dietary calcium when included in ruminant rations [58]. However, its contribution should be evaluated as part of the complete mineral profile of the diet rather than considered independently.

Phosphorus is another nutritionally important mineral present in *T. diversifolia*, with concentrations that may contribute to dietary phosphorus supply when incorporated into appropriately balanced rations [71]. Phosphorus is involved in skeletal integrity, energy metabolism, nucleic acid synthesis, growth, and reproduction [17]. An additional agronomic characteristic of *T. diversifolia* is its ability to acquire and mobilize phosphorus in tropical soils, potentially linking forage production with nutrient cycling and soil fertility improvement [24].

Potassium and magnesium in *T. diversifolia* may further contribute to the mineral supply of ruminants. Potassium is involved in osmotic regulation, acid-base balance, nerve transmission, and muscle function, whereas magnesium participates in numerous enzymatic reactions, energy metabolism, and neuromuscular function. Adequate magnesium intake is particularly important for maintaining normal physiological functions, and

insufficient magnesium intake may increase the risk of hypomagnesemia and associated disorders such as grass tetany in susceptible ruminants [69, 71]. Nevertheless, the potential contribution of *T. diversifolia* to magnesium supply should be evaluated based on its actual mineral concentration, bioavailability, and the overall dietary mineral balance.

Information regarding the vitamin composition of *T. diversifolia* remains limited. Available evidence primarily concerns carotenoids, including compounds with provitamin A activity, whereas quantitative information on other vitamins remains scarce [62]. Consequently, the contribution of *T. diversifolia* to the vitamin supply of ruminants cannot yet be characterized as comprehensively as its mineral contribution. Further studies are required to quantify individual vitamins and determine how genotype, environmental conditions, maturity, preservation, and post-harvest processing affect their concentrations, stability, and bioavailability.

The mineral composition of *T. diversifolia* may have practical implications for ruminant nutrition because calcium and phosphorus contribute to skeletal development and maintenance, whereas potassium and magnesium support normal muscular, nervous, and metabolic functions [54, 57]. These attributes may be particularly relevant for growing and lactating animals, whose mineral requirements are elevated. However, the presence of these minerals in the forage does not necessarily eliminate the need for mineral supplementation, because supplementation requirements depend on forage composition, mineral bioavailability, the remainder of the diet, production level, and animal requirements.

Similarly, although *T. diversifolia* can contribute calcium and phosphorus to diets for lactating animals, evidence is insufficient to conclude that its inclusion alone can prevent disorders such as hypocalcemia or consistently maintain milk production without supplementary minerals [70]. The mineral contribution of the forage should therefore be incorporated into ration formulation based on the overall dietary mineral balance. Given the limited quantitative evidence regarding its vitamin composition, claims concerning B vitamins and their direct effects on feed efficiency or productivity also require further validation.

Feeding studies involving goats and dairy cattle have reported favorable responses in nutrient digestibility and productive performance following supplementation with *T. diversifolia* [14, 49, 67]. However, these responses cannot be attributed solely to its mineral composition because the plant simultaneously supplies protein, carbohydrates, minerals, and secondary metabolites. Therefore, the nutritional effects of *T. diversifolia* should be interpreted in the context of its overall nutrient composition and the characteristics of the complete diet.

In addition to nutrients, *T. diversifolia* contains secondary metabolites, including tannins and saponins, some of which have demonstrated antimicrobial activity [72]. However, evidence of antimicrobial activity should not be interpreted as demonstrating that dietary *T. diversifolia* can replace therapeutic or prophylactic antibiotics in livestock. Further *in vivo* research is required to determine whether these compounds exert biologically relevant antimicrobial effects at practical dietary inclusion levels without adversely affecting nutrient utilization or rumen microbial activity.

In regions where conventional forage resources are deficient in essential minerals, *T. diversifolia* may provide a locally available supplementary source of several nutritionally important elements [73]. Its potential contribution may be particularly relevant during periods of forage scarcity or declining forage quality. Nevertheless, variation in mineral concentrations among soils, environments, stages of maturity, and processing conditions emphasizes the importance of feed analysis and balanced ration formulation rather than assuming that *T. diversifolia* consistently satisfies mineral requirements.

The nutritional value of *T. diversifolia* may also be enhanced through its incorporation with locally available agro-industrial by-products in balanced diets. Studies combining *T. diversifolia* with sugarcane-based feeds and avocado-processing residues have reported favorable effects on nutrient digestibility, rumen fermentation, and animal performance, indicating potential complementary nutritional effects while supporting the utilization of locally available feed resources [9, 24, 30, 74]. Nevertheless, additional *in vivo* studies are required to establish appropriate inclusion levels, characterize nutrient interactions, and validate these complementary effects under different production conditions.

COMPARISON WITH OTHER TROPICAL FORAGES

Compared with other forage resources, *T. diversifolia* possesses a combination of nutritional and agronomic characteristics that supports its potential use in tropical ruminant production. Comparisons with Napier grass (*Pennisetum purpureum*) and alfalfa (*Medicago sativa*) demonstrate differences in CP, fiber concentration, digestibility, mineral composition, environmental adaptability, and secondary metabolites. However, these

comparisons should be interpreted cautiously because forage composition varies with cultivar, maturity, soil fertility, climatic conditions, harvesting practices, and analytical methods.

The CP concentration of *T. diversifolia* has been reported to range from approximately 19.3% to 22.9%, which is comparable to the reported range of 15%–20% for alfalfa [51, 75]. In contrast, Napier grass has been reported to contain approximately 7%–12% CP [74]. The relatively high CP concentration of *T. diversifolia* therefore supports its potential as a supplementary protein source in tropical production systems where basal forage diets are deficient in protein [73]. Nevertheless, CP concentration alone does not determine protein value because ruminal degradability, amino acid composition, digestibility, and post-ruminal protein supply must also be considered.

The NDF concentration of *T. diversifolia* has been reported at approximately 45.4%, whereas values exceeding 60% have been reported for Napier grass [67]. Because NDF concentration and digestibility influence rumen fill, voluntary intake, and nutrient utilization, the moderate NDF concentration of *T. diversifolia* may contribute to its favorable feeding characteristics. However, forage digestibility cannot be predicted solely from NDF concentration because lignification, maturity, particle size, processing, and the composition of the complete diet also influence nutrient utilization [14].

T. diversifolia also provides nutritionally important minerals, including calcium, phosphorus, potassium, and magnesium. Alfalfa similarly has a favorable mineral profile; therefore, the relative mineral value of these forages depends on the concentrations and bioavailability of individual minerals and the requirements of the target animals [73, 76]. Comparisons with Napier grass should likewise consider environmental and agronomic variation rather than assuming uniform mineral deficiencies across cultivars and production environments.

The *in vitro* DM digestibility (IVDMD) of *T. diversifolia* has been reported to range from approximately 64.56% to 65%, indicating favorable potential digestibility relative to some tropical grasses [17, 74]. Greater digestibility can increase the proportion of nutrients potentially available to the animal; however, *in vitro* estimates should not be interpreted as direct evidence of superior productive performance under practical feeding conditions. Feeding studies in dairy goats have reported favorable responses in milk production and quality following dietary inclusion of *T. diversifolia* [57], supporting further evaluation of its practical feeding value.

The combination of relatively high CP and moderate fiber concentrations may contribute to efficient nutrient utilization when *T. diversifolia* is incorporated appropriately into balanced ruminant diets [75]. This characteristic may be particularly valuable in resource-constrained production systems where conventional protein supplements are costly or unavailable. Nevertheless, direct claims that animals require less total feed to achieve greater weight gain or milk production than when consuming conventional forages require controlled comparative evidence and should not be inferred solely from chemical composition.

Another characteristic distinguishing *T. diversifolia* from many conventional forage resources is the presence of bioactive secondary metabolites, including tannins and saponins. These compounds can influence ruminal microbial populations and fermentation pathways associated with methanogenesis [10, 77]. Dietary inclusion of *T. diversifolia* has been associated with reduced methane production under some experimental conditions [30]. The magnitude and consistency of this response, however, depend on dietary inclusion level, secondary metabolite concentration, basal diet composition, and experimental conditions.

Agronomically, *T. diversifolia* can establish under a range of soil conditions, including acidic and relatively low-fertility soils, supporting its potential use in challenging tropical environments. Compared with forage species requiring greater soil fertility or management inputs, this adaptability may offer advantages in resource-limited production systems [76, 78]. Nevertheless, productivity and forage quality remain dependent on local soil, climate, genotype, harvesting frequency, and management conditions, and its adaptability should not be interpreted as complete independence from water or nutrient availability.

Overall, *T. diversifolia* offers a combination of relatively high CP concentration, moderate fiber content, favorable potential digestibility, nutritionally important minerals, environmental adaptability, and bioactive secondary metabolites. Feeding studies indicate that it can partially replace conventional forage or concentrate ingredients without adversely affecting growth or milk production when included at appropriate dietary levels [14]. These characteristics support its potential as an alternative forage for tropical livestock systems, particularly where access to high-quality conventional feeds is constrained.

However, the advantages of *T. diversifolia* should be evaluated alongside its nutritional and management limitations. In particular, tannins and saponins may exert beneficial effects at appropriate concentrations but can also reduce nutrient utilization when present at excessive levels. Therefore, practical use of *T. diversifolia* should

consider dietary inclusion level, nutrient composition, digestibility, secondary metabolite concentrations, environmental conditions, and overall ration formulation. Its value relative to Napier grass, alfalfa, and other forage resources should consequently be assessed according to the specific nutritional, agronomic, economic, and environmental conditions of the production system [14, 24, 79, 80].

IMPROVEMENT IN ANIMAL GROWTH AND WEIGHT GAIN

The inclusion of *T. diversifolia* in ruminant diets has demonstrated potential to support growth and body weight gain, particularly in tropical and resource-limited production systems. These responses are associated with its relatively high nutrient density, protein concentration, and digestibility, although the magnitude of the effects depends on animal species, physiological status, basal diet, inclusion level, and feeding duration.

The relatively high protein content of *T. diversifolia* is an important characteristic supporting its use in diets for growing ruminants. Reported CP concentrations range from approximately 19.3% to 22.9%, values comparable to those of several protein-rich tropical forages [70, 75]. This characteristic is particularly relevant in tropical production systems where basal diets may be deficient in protein. In addition, its amino acid profile contributes substrates required for tissue protein synthesis and other metabolic processes associated with growth [14].

Digestibility is another important determinant of the feeding value of *T. diversifolia*. The forage has demonstrated favorable IVDMD, indicating that a substantial proportion of its nutrients may be available for microbial fermentation and subsequent utilization by the animal [81]. Improved digestibility can enhance nutrient availability and contribute to productive responses when *T. diversifolia* is incorporated into nutritionally balanced diets. Feeding trials in goats and cattle have reported favorable body weight responses following dietary inclusion of *T. diversifolia* [57].

Comparisons with conventional tropical forages also indicate potential advantages associated with the nutrient composition of *T. diversifolia*. Napier grass, for example, generally contains less CP and more structural fiber, although its composition varies considerably with maturity and management [74]. Studies comparing *T. diversifolia* with other tropical forage resources have reported favorable body weight responses, supporting its potential as a supplementary forage for growing ruminants [82]. Nevertheless, differences in animal performance should not be attributed exclusively to a single forage characteristic because overall diet composition, intake, digestibility, and nutrient balance collectively determine growth responses.

The productive benefits of *T. diversifolia* are not restricted to growing animals. Studies in lactating cattle have reported that its dietary inclusion can maintain or improve milk production under specific feeding conditions [70]. Similarly, feeding studies involving Etawa crossbred goats have reported favorable effects on milk production and composition when *T. diversifolia* was incorporated into the diet [14]. These findings indicate that the forage may provide nutrients that support different productive functions when appropriately incorporated into balanced rations.

Beyond its direct nutritional contribution, *T. diversifolia* may indirectly support forage-based livestock production through its use in soil fertility management. Incorporation of its biomass as green manure can increase the availability of nutrients, including phosphorus and nitrogen, and thereby contribute to soil nutrient cycling and subsequent plant growth [69]. Such agronomic functions may complement its direct use as livestock feed within integrated crop–livestock systems [11].

The adaptability of *T. diversifolia* to diverse soil and climatic conditions further supports its potential as a forage resource. Its capacity to grow in relatively low-fertility and acidic soils and tolerate periods of limited water availability may provide advantages in tropical and resource-constrained environments [76, 83]. However, this adaptability does not necessarily guarantee a stable year-round forage supply because biomass production remains influenced by rainfall, soil fertility, harvesting frequency, genotype, and other management factors.

Although favorable effects on body weight gain and nutrient utilization have been reported, the magnitude and consistency of these responses vary among studies. Current evidence supports the potential use of *T. diversifolia* as a partial replacement for conventional protein-rich feeds; however, additional long-term studies are required to determine optimal dietary inclusion rates and evaluate carcass characteristics, reproductive performance, feed efficiency, and long-term productive responses under different production systems [23, 30, 70].

IMPACT ON MILK YIELD AND QUALITY

Dietary inclusion of *T. diversifolia* has also been investigated for its effects on milk production and composition in dairy ruminants. Available studies indicate that the forage can support milk yield and may influence

selected milk-quality characteristics when incorporated at appropriate levels into nutritionally balanced diets. These responses are likely related to its protein concentration, digestibility, fermentable nutrient supply, and effects on ruminal fermentation.

Studies in dairy cattle have reported greater milk production following supplementation with *T. diversifolia* under specific dietary conditions [70]. Its relatively high CP concentration and favorable digestibility may increase the availability of nutrients required for lactation. However, responses in milk yield depend on several interacting factors, including DM intake, basal diet composition, stage of lactation, dietary inclusion level, nutrient digestibility, and overall energy and protein balance. Therefore, increases in milk production cannot be attributed solely to the CP concentration of *T. diversifolia*.

Ruminal fermentation of dietary carbohydrates generates VFAs, particularly acetate, propionate, and butyrate, which constitute major sources of metabolizable energy for ruminants. Acetate also serves as an important precursor for de novo milk fat synthesis, whereas propionate contributes to hepatic gluconeogenesis and glucose supply [9]. Dietary inclusion of *T. diversifolia* has been associated with changes in ruminal fermentation and VFA production [30]. These effects may contribute to nutrient and energy availability for lactation, although fermentation responses depend on the composition of the complete diet.

Dietary inclusion of *T. diversifolia* has also been investigated for its potential influence on the fatty acid composition of milk. Some studies have reported changes in milk polyunsaturated fatty acid (PUFA) concentrations following supplementation [70]. Such changes may influence the nutritional characteristics of milk; however, the magnitude and consistency of these responses require further evaluation under standardized feeding conditions. In particular, claims regarding direct health benefits to consumers require evidence beyond changes in milk fatty acid composition alone.

Adequate dietary fiber is essential for maintaining ruminal function and supporting milk fat synthesis. Diets containing sufficient physically effective fiber promote chewing and salivary buffering and help maintain ruminal conditions favorable for fiber digestion, whereas inadequate effective fiber can increase the risk of subacute ruminal acidosis (SARA) [84, 85]. Although *T. diversifolia* contributes fiber to the diet, its ability to maintain ruminal pH or prevent SARA cannot be inferred solely from its total fiber concentration. Its effects should instead be evaluated in relation to particle size, physically effective fiber, inclusion level, and the overall forage-to-concentrate ratio.

The protein supplied by *T. diversifolia* may also contribute to milk protein synthesis. Its dietary protein can provide nitrogen for rumen microorganisms, thereby supporting microbial protein synthesis when sufficient fermentable energy is available. Microbial protein subsequently passes to the small intestine, where digestion releases amino acids that contribute to the metabolizable protein supply available for maintenance and milk protein synthesis [86]. Studies in dairy ruminants have reported changes in milk protein concentration following inclusion of *T. diversifolia* [57]; however, these responses depend on the balance between ruminally available nitrogen, fermentable energy, RUP, and the amino acid supply reaching the small intestine.

The practical value of *T. diversifolia* in dairy production is particularly relevant in tropical and resource-limited systems where conventional protein supplements may be costly or seasonally unavailable. Its adaptability to relatively unfavorable growing conditions and potential to partially replace conventional feed ingredients may reduce dependence on purchased feeds while maintaining productive performance [57, 68, 82]. Studies involving Pesisir cattle and Etawa crossbred goats have reported favorable productive responses following dietary supplementation with *T. diversifolia*, supporting further evaluation of its use in locally adapted dairy feeding systems.

Available evidence indicates that *T. diversifolia* may be strategically incorporated into feeding programs during physiologically demanding periods, including growth and lactation. Nevertheless, responses depend on the nutritional characteristics of the basal diet and the quantity and form in which *T. diversifolia* is supplied. Future studies should therefore establish optimal inclusion levels across different dairy production systems and evaluate long-term effects on milk yield, milk composition, nutrient-use efficiency, and economically relevant product characteristics. Further investigation of potential carry-over effects on milk bioactive components and nutritional composition may also clarify whether *T. diversifolia* can contribute to precision feeding strategies and value-added dairy production [23, 24, 70].

HEALTH, IMMUNE FUNCTION, AND DISEASE RESISTANCE BENEFITS

T. diversifolia contains several classes of bioactive compounds, including phenolic compounds, flavonoids,

sesquiterpene lactones, and other constituents with antioxidant, anti-inflammatory, and antimicrobial activities. These properties have generated interest in the potential use of *T. diversifolia* to support animal health and immune function. However, much of the available evidence is derived from extract-based experiments, *in vitro* studies, or non-ruminant models; therefore, the extent to which these biological activities translate into clinically relevant health benefits in ruminants remains to be established.

Antioxidant activity is among the most frequently reported biological properties of *T. diversifolia*. Oxidative stress occurs when the production of reactive oxygen species exceeds endogenous antioxidant defenses, potentially resulting in oxidative damage to lipids, proteins, and nucleic acids and subsequently impairing cellular and immune functions. Studies using ethanolic extracts of *T. diversifolia* have demonstrated antioxidant activity in experimental models [87]. These findings indicate that the plant contains compounds capable of exerting antioxidant activity; however, direct evidence that dietary inclusion produces comparable systemic antioxidant responses in ruminants remains limited.

Phenolic compounds present in *T. diversifolia* have also been investigated for their antioxidant, anti-inflammatory, and potential immunomodulatory properties [88]. Such compounds can influence oxidative and inflammatory pathways and may therefore contribute to the biological activity attributed to the plant. Nevertheless, the effects of phenolic compounds depend on their chemical structure, concentration, bioavailability, metabolism, and interactions with other dietary components. Consequently, evidence obtained from isolated compounds or extracts should not be directly extrapolated to whole-plant feeding responses in ruminants without appropriate *in vivo* validation.

Sesquiterpene lactones constitute another important group of bioactive compounds reported in *T. diversifolia*. These compounds have demonstrated antimicrobial and anti-inflammatory activities under experimental conditions [89]. Such findings suggest potential applications in animal nutrition and health; however, current evidence does not establish that feeding *T. diversifolia* prevents infectious diseases or reduces the need for antimicrobial treatment in livestock. The biological relevance, effective dietary concentrations, and safety of these compounds therefore require further investigation in ruminant feeding studies.

In vitro antimicrobial assays have demonstrated inhibitory activity against bacteria including *Staphylococcus aureus* and *Pseudomonas aeruginosa* [72]. These observations provide evidence of antimicrobial activity under experimental conditions and support continued investigation of the plant as a potential source of bioactive feed constituents. However, antimicrobial effects observed with concentrated plant extracts should be distinguished from the effects of feeding intact or processed forage. Controlled *in vivo* studies are required to determine whether practical dietary inclusion levels can influence pathogen populations, gastrointestinal microbial ecology, or disease outcomes in ruminants.

The antioxidant and anti-inflammatory properties reported for *T. diversifolia* may also have implications for metabolic health because oxidative stress and chronic inflammation can adversely affect physiological function and productivity. Bioactive compounds capable of modulating these processes could theoretically contribute to improved metabolic resilience; however, direct evidence in ruminants remains insufficient. Further studies are therefore required to determine whether dietary supplementation with *T. diversifolia* produces measurable changes in oxidative stress biomarkers, inflammatory mediators, metabolic status, or productive performance.

The potential health-promoting properties of *T. diversifolia* may be particularly relevant in tropical livestock systems, where animals can be exposed to nutritional, climatic, and infectious stressors. Its simultaneous provision of nutrients and bioactive compounds provides a rationale for investigating whether dietary inclusion may influence physiological responses to such conditions [57]. Nevertheless, claims regarding enhanced immunity or disease resistance should be based on direct measurements of immune and health outcomes rather than inferred from phytochemical composition alone.

The traditional ethnoveterinary use of *T. diversifolia* further supports scientific interest in its potential biological activities [69]. However, ethnoveterinary use should be regarded as a basis for hypothesis generation rather than as evidence of therapeutic efficacy. Establishing practical applications in modern livestock systems requires standardized characterization of plant material, identification of active constituents, determination of safe inclusion levels, and confirmation of biological effects under controlled feeding conditions.

Despite increasing evidence of antioxidant, antimicrobial, and anti-inflammatory activities, most available data remain derived from *in vitro* experiments, extract-based studies, or non-ruminant models [47, 72, 79]. Consequently, the immunomodulatory potential of *T. diversifolia* in ruminants requires confirmation through well-designed *in vivo* studies evaluating dietary inclusion level, feeding duration, safety, rumen and intestinal

microbiota, and immune biomarkers, including cytokines, immunoglobulins, and indicators of oxidative status. Future investigations may also examine microbiome-mediated pathways and systemic host–microbial interactions to clarify the mechanisms through which dietary *T. diversifolia* could influence animal health [90, 91].

METHANE REDUCTION POTENTIAL

T. diversifolia has attracted considerable interest as a potential dietary strategy for mitigating enteric methane emissions from ruminants. Methane is generated predominantly by methanogenic archaea during anaerobic fermentation in the rumen and represents both an environmental concern and a loss of dietary energy. Therefore, forage resources capable of modifying ruminal fermentation while maintaining animal productivity are of increasing interest in sustainable livestock production.

The methane-mitigating potential of *T. diversifolia* has been associated primarily with its secondary metabolites, particularly condensed tannins and saponins, which can influence rumen microbial populations and fermentation pathways. These compounds may reduce protozoal populations, alter interspecies hydrogen transfer, and indirectly affect methanogenic activity [72]. Rivera *et al.* [70] evaluated dual-purpose dairy cows fed diets containing 15%–30% *T. diversifolia* under *in vivo* conditions and reported reductions in enteric methane emissions while maintaining milk production. Evidence regarding the methane mitigation potential of *T. diversifolia* is summarized in Table 4 [14, 17, 30, 70, 75, 92].

Table 4: Potential of *Tithonia diversifolia* for methane reduction.

Animal/experimental model	Dietary inclusion of <i>T. diversifolia</i>	Main findings	Proposed mechanism	Reference
<i>In vitro</i> rumen fermentation	Fermented <i>T. diversifolia</i>	Improved rumen fermentation characteristics and nutrient digestibility, with lower methane production than the untreated control	Increased nutrient availability and modulation of rumen fermentation following fermentation	[14]
<i>In vitro</i> rumen fermentation	Increased RDP using <i>T. diversifolia</i>	Improved nutrient digestibility and rumen fermentation, supporting more efficient microbial utilization and lower methane formation	Enhanced microbial protein synthesis and fermentation efficiency	[17]
<i>In vitro</i> fermentation (BMR sorghum + <i>T. diversifolia</i>)	Mixed ration	Increased digestibility and VFA production while reducing methane production	Improved fermentation efficiency and hydrogen utilization	[30]
Dual-purpose dairy cows (<i>in vivo</i>)	15% of diet DM	Methane emissions decreased by 6.8%, while milk production increased	Secondary metabolites, including tannins and saponins, modulated rumen fermentation and reduced methanogenesis	[70]
<i>In vitro</i> fermentation	Agroforestry forage species, including <i>T. diversifolia</i>	Lower GHG production with favorable rumen fermentation characteristics	Improved fermentation efficiency associated with bioactive secondary metabolites	[75]
Sheep (<i>in vivo</i>)	Diet containing 90, 270, and 450 g/kg DM of <i>T. diversifolia</i> hay	No significant effect on CH ₄ and other GHG emissions, while digestibility responses varied with dietary inclusion level	Changes in ruminal fermentation and nutrient digestibility associated with increasing <i>T. diversifolia</i> inclusion	[92]

BMR = brown midrib; DM = dry matter; GHG = greenhouse gas; RDP = rumen-degradable protein; VFA = volatile fatty acid.

Secondary metabolites in *T. diversifolia* may also influence the pattern of ruminal VFA production. Condensed tannins and other bioactive compounds can alter fermentation pathways, potentially increasing the relative contribution of propionate while reducing acetate-associated hydrogen generation [71]. Because propionate formation consumes reducing equivalents that might otherwise be available for methanogenesis, a shift toward propionate can contribute to lower methane production. Nevertheless, fermentation responses depend on the concentration and chemical characteristics of secondary metabolites, dietary inclusion level, basal diet, and adaptation of the rumen microbial community.

Additional *in vivo* evidence supports the potential methane-mitigating effect of *T. diversifolia*. In dual-purpose cows, dietary inclusion at 30% was associated with lower methane emissions than a conventional control diet [70]. These effects have been attributed to secondary metabolites capable of modifying microbial fermentation and hydrogen utilization. However, the precise mechanisms remain incompletely characterized, and

reductions in methane production should not be attributed solely to direct inhibition of methanogens without supporting microbial or molecular evidence.

The potential reduction of enteric methane emissions through dietary inclusion of *T. diversifolia* has broader implications for the environmental sustainability of ruminant production. Available studies indicate that methane responses vary considerably according to inclusion level, basal diet composition, animal species, forage processing, and experimental conditions [14]. Therefore, the magnitude of methane mitigation observed in individual studies should not be generalized across production systems without considering these interacting factors.

Beyond its role as livestock feed, *T. diversifolia* may contribute to nutrient cycling when its biomass is incorporated into soil as green manure. Its biomass contains substantial amounts of nitrogen, phosphorus, and potassium, and its incorporation into soil can contribute to nutrient return and soil fertility [53]. This multifunctional role may facilitate integration of *T. diversifolia* into crop–livestock or silvopastoral systems in which forage production and soil nutrient management are considered together. However, reductions in synthetic fertilizer use or improvements in soil carbon sequestration require system-specific evaluation and should not be assumed solely from biomass incorporation.

The cultivation of *T. diversifolia* may also provide selected ecosystem services under appropriate management. Its rapid growth, tolerance of diverse soil conditions, and floral resources may support soil cover and pollinator activity, while its biomass production may contribute to erosion control and nutrient cycling [80]. Nevertheless, because the species can exhibit invasive behavior in some environments, biodiversity benefits should be assessed alongside potential ecological risks, and controlled cultivation is necessary to prevent unintended spread.

From a production perspective, *T. diversifolia* may provide both nutritional and environmental advantages where it can be locally cultivated and incorporated into balanced diets. Its potential to reduce methane production while providing forage nutrients may be particularly relevant for tropical and subtropical livestock systems. However, comparisons with synthetic methane-mitigating feed additives should consider efficacy, dose consistency, animal performance, land requirements, labor, seasonal availability, and the potential effects of secondary metabolites on nutrient utilization [80].

Although the methane-mitigating potential of *T. diversifolia* has been demonstrated under several experimental conditions, the magnitude of the response remains variable. Current evidence indicates that condensed tannins and saponins may modify rumen microbial communities and fermentation patterns, including interactions involving protozoa and hydrogen transfer, which may subsequently influence methanogenic archaea and methane formation [79, 93]. Methanogenic archaea are the principal microorganism responsible for methane production in the rumen, whereas protozoa may influence methanogenesis indirectly through long-term *in vivo* studies integrating rumen microbiome profiling, metagenomic approaches, direct methane measurements, and dose–response evaluations across different animal species and production systems. Future studies should also investigate the potential complementary use of *T. diversifolia* with other methane mitigation strategies, including probiotics and essential oils, while evaluating animal performance, nutrient utilization, and whole-farm GHG emissions within silvopastoral systems [7, 8, 94].

COMMON ANTI-NUTRITIONAL COMPOUNDS

T. diversifolia is a nutrient-rich forage containing substantial amounts of protein and minerals; however, its feeding value may be constrained by several anti-nutritional compounds, particularly phytic acid, tannins, and oxalates. These compounds can affect nutrient availability, palatability, and digestibility, depending on their concentrations, dietary inclusion level, processing method, and the composition of the complete ration. Understanding their nutritional effects is therefore important for the safe and effective incorporation of *T. diversifolia* into ruminant diets.

Phytic acid, or myo-inositol hexakisphosphate, is a major storage form of phosphorus in plant tissues. It is capable of chelating minerals such as calcium, iron, and zinc and forming complexes that may reduce their bioavailability [30]. The phytic acid concentration of *T. diversifolia* has been reported at approximately 7.19 mg/100 g [29]. However, the nutritional significance of this concentration in ruminants depends on total dietary intake, ruminal degradation, microbial phytase activity, and interactions with other dietary components.

Although rumen microorganisms can degrade phytate to varying degrees, high dietary concentrations may

still influence mineral utilization. Phytic acid may also contribute to reduced palatability under certain conditions, potentially affecting voluntary feed intake [29]. Biological processing, particularly fermentation with *L. bulgaricus*, has therefore been investigated as a strategy to decrease phytic acid concentrations in *T. diversifolia*. Microbial phytase activity during fermentation can hydrolyze phytate and release phosphorus and associated minerals, thereby potentially improving nutrient availability [58].

Tannins are polyphenolic compounds widely distributed among forage plants, including *T. diversifolia*. Their nutritional effects are concentration-dependent. At moderate concentrations, tannins may provide beneficial effects by modifying ruminal protein degradation and microbial fermentation; however, excessive tannin concentrations can reduce palatability, protein digestibility, and nutrient utilization. Tannins form complexes with proteins and other macromolecules, which can decrease their accessibility to rumen microorganisms and digestive enzymes [30]. They may also interact with minerals, including iron, and at high concentrations can adversely affect feed intake and digestive function [72].

The tannin content of *T. diversifolia* may therefore influence both its nutritional benefits and limitations. Excessive concentrations may reduce voluntary feed intake and protein utilization, particularly in animals with high nutrient requirements. Processing approaches such as fermentation and dietary dilution through combination with low-tannin forage resources have been investigated to reduce these adverse effects [30]. Nevertheless, tannins should not be regarded exclusively as anti-nutritional compounds because their effects depend on tannin type, concentration, dietary context, and animal species.

Oxalates are organic acids present in several forage species, including *T. diversifolia*. They can bind calcium to form insoluble calcium oxalate complexes, potentially decreasing calcium availability. Calcium is essential for skeletal development, neuromuscular function, and lactation; therefore, excessive dietary oxalate exposure may have nutritional and metabolic consequences. High oxalate intake has also been associated with renal and other metabolic disturbances in susceptible animals [95].

The nutritional significance of oxalates in *T. diversifolia* depends on their concentration, total dietary calcium supply, adaptation of rumen microorganisms, and duration of exposure. Excessive oxalate intake relative to available calcium can impair calcium metabolism and, under severe conditions, contribute to oxalate toxicity. Processing techniques, including drying and fermentation, have been investigated as approaches to reduce oxalate concentrations and improve the nutritional suitability of oxalate-containing forage resources [96].

Collectively, phytic acid, tannins, and oxalates may influence nutrient utilization through different mechanisms. Phytic acid can reduce the availability of several minerals through chelation, whereas oxalates predominantly affect calcium availability. Tannins primarily influence protein utilization through their capacity to bind proteins, although they may also interact with minerals and other dietary constituents [97, 98]. The extent of these effects in ruminants is influenced by ruminal microbial adaptation and the composition of the complete diet; therefore, their nutritional significance should not be inferred solely from their concentrations in the forage.

High concentrations of these anti-nutritional compounds may consequently limit the proportion of *T. diversifolia* that can be incorporated safely and effectively into ruminant diets. Appropriate processing, balanced dietary formulation, gradual adaptation, and suitable inclusion levels are important for minimizing potential adverse effects while retaining the nutritional and functional benefits of the forage [30].

STRATEGIES FOR REDUCING ANTI-NUTRITIONAL FACTORS

Several processing strategies have been investigated to decrease anti-nutritional compounds in *T. diversifolia* and other plant-based feeds. Fermentation, ensiling, microbial inoculation, and related biological treatments can alter phytic acid, tannin, and fiber fractions and may improve nutrient availability and forage preservation. However, the effectiveness of these approaches depends on the microbial strain, substrate characteristics, fermentation conditions, treatment duration, and initial concentrations of anti-nutritional compounds.

Fermentation is among the most frequently investigated strategies for reducing phytic acid in plant-based feeds. In *T. diversifolia*, fermentation with *L. bulgaricus* has been reported to decrease phytic acid concentrations [9]. Microbial phytase produced during fermentation can hydrolyze phytate into lower inositol phosphates and inorganic phosphorus, potentially releasing minerals previously bound in phytate complexes [99]. Fermentation of *T. diversifolia* with *L. bulgaricus* has been reported to reduce phytic acid concentrations by up to 77% under the experimental conditions evaluated [29]. Such reductions may improve the nutritional value of the processed forage, although changes in actual mineral absorption and animal performance require confirmation under feeding conditions.

Fermentation may also modify tannin concentrations and their interactions with dietary protein. Alasha'ab *et al.* [100] reported reductions in tannin concentrations following bacterial fermentation of legumes, together with improvements in nutritional characteristics. These findings demonstrate the potential of microbial fermentation to modify tannin-containing plant materials; however, effects observed in legumes should not be assumed to occur to the same extent in *T. diversifolia*. Direct studies using *T. diversifolia* are required to determine the magnitude of tannin degradation and its consequences for protein digestibility.

Different microorganisms may produce enzymes capable of degrading or modifying anti-nutritional compounds. *Lactobacillus plantarum* and *Bacillus subtilis*, for example, have been investigated for their ability to decrease phytic acid and tannin concentrations and improve nutrient digestibility in fermented feeds [101]. Their application to *T. diversifolia* may therefore be promising, but potential synergistic effects of mixed microbial cultures should be demonstrated experimentally rather than inferred from studies involving other substrates.

Ensiling provides another practical strategy for forage preservation and may simultaneously alter selected anti-nutritional compounds. During ensiling, anaerobic fermentation lowers pH and modifies plant constituents, potentially improving preservation, palatability, and nutrient utilization. Studies on *Leucaena leucocephala* have demonstrated reductions in certain anti-nutritional factors after ensiling [102]. These findings provide relevant comparative evidence for tannin-containing tropical forages but do not necessarily establish identical responses in *T. diversifolia*.

Ensiling *T. diversifolia* with readily fermentable additives such as molasses has been investigated to promote desirable fermentation and improve preservation. Additives may enhance lactic acid production and accelerate the decline in silage pH, thereby improving fermentation quality. Reports also indicate that ensiling with additives such as molasses or urea can improve palatability and digestibility and may decrease selected anti-nutritional compounds [58]. Nevertheless, the magnitude of these effects depends strongly on ensiling conditions, additive concentration, DM content, and storage duration.

Microbial inoculants may further improve the fermentation characteristics of plant-based feeds. In addition to *L. plantarum* and *B. subtilis*, *Saccharomyces cerevisiae* has been investigated for its potential role in improving feed quality. Zhu *et al.* [103] reported that microbial treatments reduced tannin and phytic acid concentrations in soybean meal and improved its digestibility. Although these findings support the broader potential of microbial processing, their direct applicability to *T. diversifolia* requires specific validation because substrate composition can strongly influence fermentation responses.

Solid-state fermentation (SSF) is another biological processing approach in which microorganisms grow on moist solid substrates with little or no free-flowing water. SSF has been used to reduce anti-nutritional compounds and improve the nutritional characteristics of plant-derived feeds. Studies using lactic acid bacteria (LAB) in soybean meal have demonstrated reductions in trypsin inhibitors and phytic acid and improvements in protein digestibility [104]. The application of SSF to *T. diversifolia* therefore represents a potentially useful processing approach, although direct evidence should be distinguished from findings obtained with soybean meal or other substrates.

Reduction of anti-nutritional factors through appropriate processing may have practical nutritional benefits. Lower phytic acid concentrations can increase the proportion of phosphorus and associated minerals potentially available for utilization, whereas reduced tannin concentrations may decrease excessive protein-binding and improve protein accessibility. These effects may be particularly relevant for growing and lactating animals with comparatively high nutrient requirements. Nevertheless, improvements in chemical composition do not necessarily translate directly into proportional improvements in nutrient absorption or productive performance, emphasizing the need for controlled *in vivo* evaluation.

Microbial fermentation and ensiling may also improve the use of locally available forage resources by increasing preservation stability and modifying compounds that constrain feeding value. Such approaches could contribute to more efficient utilization of *T. diversifolia* in tropical livestock systems and may reduce dependence on more expensive feed ingredients. However, economic and environmental benefits depend on the cost, labor requirements, infrastructure, microbial inoculants, processing losses, and productive responses associated with each treatment [14].

The effectiveness of these processing strategies varies according to microbial strain, fermentation duration, substrate composition, moisture content, temperature, inoculum concentration, and other processing conditions. Fermentation with *L. bulgaricus* has been reported to reduce phytic acid concentrations by up to 77% in *T. diversifolia* [29], whereas studies using *L. plantarum* and mixed microbial cultures suggest potential reductions in

tannins and improvements in protein digestibility in fermented plant materials. Ensiling with appropriate additives may simultaneously preserve forage and modify selected anti-nutritional compounds. Nevertheless, direct comparisons among processing techniques should be interpreted cautiously because of substantial differences in experimental substrates, inocula, incubation periods, and analytical protocols [9, 14, 29, 105, 106]. Future studies should therefore compare processing approaches under standardized conditions and determine whether reductions in anti-nutritional factors translate into improved nutrient bioavailability, animal performance, safety, and economic feasibility under practical feeding conditions.

ROLE OF FERMENTATION IN ENHANCING NUTRITIONAL QUALITY

Fermentation using LAB, particularly *L. bulgaricus*, has considerable potential to improve the nutritional characteristics and preservation quality of *T. diversifolia*. Fermentation may enhance nutrient availability, reduce selected anti-nutritional factors, and improve digestibility, thereby increasing the feeding value of the forage. These effects arise through several mechanisms, including acidification of the substrate, enzymatic degradation of anti-nutritional compounds, modification of protein fractions, and production of organic acids and other fermentation metabolites.

LAB, including *L. bulgaricus* and *L. plantarum*, convert fermentable carbohydrates primarily into lactic acid, thereby reducing the pH of the fermented substrate. Acidification favors forage preservation and can alter the solubility and chemical forms of certain minerals [105]. Under appropriate fermentation conditions, the lower pH and microbial enzymatic activity may also facilitate degradation of selected anti-nutritional compounds and improve the potential availability of minerals such as calcium, phosphorus, and iron in *T. diversifolia* [107]. However, greater mineral solubility does not necessarily indicate proportionally greater absorption by the animal, and this relationship requires confirmation through *in vivo* studies.

One of the most consistently reported effects of LAB fermentation is the degradation of phytic acid. Microbial phytase can hydrolyze phytate into lower inositol phosphates and inorganic phosphorus, thereby reducing its capacity to bind minerals [29]. Fermentation of *T. diversifolia* has been reported to decrease phytic acid concentrations by up to 77% under specific experimental conditions [29]. Such reductions may increase the potential availability of phosphorus and other minerals associated with phytate complexes, although the magnitude of the nutritional benefit depends on the initial phytate concentration, microbial strain, fermentation conditions, and subsequent digestion by the animal.

Fermentation may also modify tannins and their interactions with dietary protein. Tannins can form complexes with proteins and thereby reduce their accessibility to ruminal microorganisms and digestive enzymes when present at excessive concentrations. Alasha'ab *et al.* [100] reported reductions in tannin concentrations following bacterial fermentation of plant materials. These findings indicate that microbial fermentation can modify tannin-containing substrates, but the magnitude of tannin degradation and improvement in protein utilization in *T. diversifolia* should be determined directly because fermentation responses vary among plant species and treatment protocols.

Fermentation can additionally generate or modify biologically active compounds, including peptides and organic acids. Ujilestari *et al.* [108] reported changes in bioactive peptide production following fermentation with *Lactobacillus casei*. Such peptides may possess functional properties; however, evidence that they directly enhance gastrointestinal health, immune function, or nutrient absorption in ruminants remains limited [109]. Therefore, potential functional effects of fermentation-derived compounds should be distinguished from improvements in feed preservation and chemical composition that have been demonstrated more directly.

Reduction of phytic acid during LAB fermentation may improve the potential availability of calcium, iron, phosphorus, and other minerals by decreasing mineral–phytate complex formation [86]. This effect could be nutritionally relevant in production systems where basal diets provide marginal mineral concentrations. Nevertheless, the actual contribution of fermented *T. diversifolia* to mineral status depends on total dietary mineral supply, mineral bioavailability, physiological requirements, and interactions among dietary constituents.

Fermentation may also influence protein utilization through microbial proteolysis and modification of protein–polyphenol complexes. Hydrolysis of complex proteins can produce smaller peptides and free amino acids, whereas degradation or modification of tannin–protein complexes may increase protein accessibility [14]. These changes may improve the potential feeding value of fermented *T. diversifolia*; however, greater proteolysis is not universally beneficial because excessive protein degradation during fermentation may reduce the amount of nutritionally useful intact protein. Consequently, fermentation conditions should be optimized to balance anti-

nutritional factor reduction with preservation of desirable protein fractions.

Fermented forage may also introduce viable LAB and their fermentation metabolites into the digestive tract. These microorganisms and metabolites may influence gastrointestinal microbial communities, although the extent to which LAB used for forage fermentation function as probiotics after ingestion by ruminants remains uncertain [109, 110]. The rumen environment, survival of the microorganisms, dose, feeding duration, and host species all influence potential microbial effects. Therefore, LAB-fermented *T. diversifolia* should not automatically be considered a probiotic feed without evidence demonstrating viable delivery and beneficial host responses.

From a sustainability perspective, fermentation may increase the practical value of locally available *T. diversifolia* by improving preservation, reducing selected anti-nutritional factors, and potentially increasing nutrient utilization. These benefits could reduce losses associated with seasonal forage availability and improve the use of locally produced feed resources [111]. However, fermentation does not necessarily eliminate the requirement for mineral or protein supplementation, because supplementation needs remain dependent on the nutrient composition of the complete ration and animal requirements.

LAB-fermented *T. diversifolia* may consequently be considered a processed forage with potential functional characteristics rather than simply a conventional preserved feed. Its potential nutritional and biological effects warrant further investigation, particularly regarding the relationship among fermentation conditions, microbial populations, fermentation metabolites, nutrient utilization, and animal performance [112]. Similar fermentation approaches may also be applicable to other locally available plant resources, although each substrate requires independent evaluation.

From a practical perspective, fermentation and ensiling may represent relatively accessible processing technologies because they can use locally available forage and, in some cases, naturally occurring or commercially supplied microbial inoculants. Nevertheless, adoption by smallholder farmers may be constrained by the cost and availability of starter cultures, suitable storage facilities, technical knowledge, labor requirements, and the need to maintain appropriate anaerobic fermentation conditions. Future studies should therefore incorporate economic assessments, cost–benefit analyses, and farm-scale validation to determine the feasibility and scalability of these technologies under tropical production systems [111, 113, 114].

To facilitate comparison among processing technologies, Table 5 [9, 14, 29, 58, 103-106, 115] summarizes the principal processing methods evaluated for *T. diversifolia*, including their mechanisms, reported effects on anti-nutritional factors, nutritional improvements, practical advantages, and limitations. Such comparisons should account for differences in microbial inocula, processing duration, substrate composition, moisture content, additives, and analytical methods because these factors substantially influence treatment effectiveness.

Table 5: Comparison of processing methods for improving the nutritional quality of *Tithonia diversifolia*.

Processing method	Microorganisms/additives	Anti-nutritional factor reduction	Main nutritional improvements	Advantages	Reference
Fermentation	<i>Lactobacillus bulgaricus</i>	Phytic acid decrease by up to 77%	Reduced phytic acid concentration; protein digestibility was also evaluated	High reduction efficiency	[9, 29]
Fermentation	<i>Lactobacillus plantarum</i>	Reduced tannins and phytate	Improved digestibility and fermentation quality	Simple and effective	[14, 105]
Mixed microbial fermentation	LAB + <i>Bacillus</i> spp. + yeast	Reduced anti-nutritional compounds	Enhanced nutrient availability	Synergistic microbial activity	[103, 104]
Ensiling	Molasses or LAB inoculants	Reduced tannins and improved preservation	Increased palatability and nutrient conservation	Suitable for seasonal forage storage	[58, 106]
SSF	LAB/ <i>Bacillus subtilis</i>	Reduced phytate and protein-binding compounds	Higher protein utilization	Promising for functional feed development	[103, 115]

LAB = lactic acid bacteria; SSF = solid-state fermentation.

IMPLICATIONS FOR RUMINANT HEALTH AND PRODUCTIVITY

The nutritional value of *T. diversifolia* in ruminant diets can be improved by managing its anti-nutritional factors through fermentation, ensiling, and other processing approaches. Reduction or modification of phytic acid, excessive tannins, and oxalates may improve nutrient availability and digestibility, although productive responses ultimately depend on the composition of the complete diet, processing conditions, dietary inclusion level, and animal requirements.

Phytic acid can bind minerals such as calcium, iron, and zinc and thereby decrease their potential availability [29]. Fermentation with LAB, including *L. bulgaricus*, can reduce phytic acid concentrations through microbial phytase activity, potentially releasing phosphorus and other minerals from phytate complexes [116]. This biochemical change may improve the nutritional value of the processed forage; however, direct measurements of mineral absorption, retention, and animal mineral status are required before concluding that fermentation consistently improves mineral nutrition under practical feeding conditions.

Fermentation may also modify tannins and improve protein accessibility when tannin concentrations would otherwise limit nutrient utilization [117]. Because tannins can bind dietary proteins, reduction or structural modification of these compounds may decrease excessive protein complex formation. Similarly, reductions in oxalate concentrations could potentially improve calcium availability [86]. However, the magnitude of these responses depends on the initial concentrations of the compounds and the effectiveness of the processing treatment.

Processing-induced changes in anti-nutritional factors and forage composition may contribute to improved digestibility and voluntary intake. In lactating Etawa crossbreed dairy goats, inclusion of *T. diversifolia* at 16, 32, 48 or 64% of the diet, replacing *Pennisetum purpureum* in the forage component, increased nutrient intake but did not significantly affect nutrient digestibility or milk yield [57]. Such effects may reflect several simultaneous changes, including acidification, partial degradation of structural carbohydrates, modification of protein fractions, and reduction of selected anti-nutritional compounds. Accordingly, improved productive performance should not be attributed to a single fermentation mechanism.

Feeding studies have also reported favorable growth responses when *T. diversifolia* is incorporated into balanced rations. In goat, a diet containing fermented *T. diversifolia* and with mangrove hay was evaluated for nutrient intake, digestibility, and body weight gain, produced a body weight gain of 65.25 g/head/day [58]. These findings support the potential feeding value of *T. diversifolia* but should be interpreted in relation to the specific basal diet, animal type, treatment duration, and dietary formulation used in each experiment.

Improved availability of minerals and protein after processing may also support physiological functions associated with growth, metabolism, and immune competence. Calcium, iron, and zinc participate in numerous biological processes, and inadequate dietary supply can compromise normal physiological function [51]. Nevertheless, evidence that fermented *T. diversifolia* directly enhances disease resistance or reduces susceptibility to infection in ruminants remains limited. Such health claims require direct assessment using validated immune, metabolic, and clinical indicators.

LAB fermentation may generate organic acids, peptides, and other fermentation products that influence feed quality and microbial ecology [118]. These products may affect ruminal or intestinal microbial communities, but claims of improved immune function or pathogen suppression require confirmation through controlled *in vivo* studies. Future studies should evaluate microbial community composition together with nutrient digestibility, inflammatory markers, oxidative status, and productive responses to establish whether fermentation-derived changes have biologically meaningful health effects.

The use of processed *T. diversifolia* may also provide economic benefits where the forage is locally abundant and can partially replace more expensive conventional feed ingredients. Its ability to grow under relatively low-input conditions may increase its attractiveness in resource-constrained livestock systems [53]. However, reductions in feed costs cannot be assumed solely from forage availability because harvesting, chopping, inoculation, fermentation, storage, labor, DM losses, and transportation also contribute to the overall cost of feeding.

From an environmental perspective, improved utilization of locally produced forage may reduce dependence on externally sourced feeds and contribute to more integrated livestock production systems. The methane-mitigating potential of *T. diversifolia* has also been reported under certain dietary conditions [30]. However, high digestibility alone does not necessarily reduce methane emissions per unit of animal product, and environmental benefits should be quantified using appropriate measurements of enteric methane, animal productivity, land use, and whole-system GHG emissions.

Integration of *T. diversifolia* into silvopastoral and crop–livestock systems may provide additional agronomic functions, including soil cover, biomass recycling, nutrient return, and erosion control under appropriate management [119]. Nevertheless, these ecosystem benefits depend on local environmental conditions, planting density, management practices, and control of potential invasiveness. Thus, the overall value of processed *T. diversifolia* should be evaluated using an integrated framework that considers nutritional performance, animal

health, economic feasibility, and environmental outcomes.

FERMENTATION AND PROCESSING TECHNIQUES FOR *T. diversifolia*

Fermentation is widely used to improve the preservation and nutritional characteristics of feed materials through the metabolic activities of selected microorganisms. In *T. diversifolia*, fermentation has been investigated primarily as a strategy to reduce anti-nutritional compounds, improve nutrient availability, and enhance storage stability. The effectiveness of the process depends on microbial strain selection, fermentation duration, inoculum concentration, temperature, pH, oxygen availability, substrate composition, and storage conditions.

LAB are commonly used in forage fermentation because they convert fermentable carbohydrates into organic acids, particularly lactic acid, thereby decreasing substrate pH and inhibiting undesirable microorganisms. *L. plantarum* is frequently used because of its adaptability to different substrates and fermentation environments [14]. In addition to LAB, fungi such as *Aspergillus ficuum* may be incorporated into selected fermentation systems because of their capacity to produce enzymes, including phytase. *L. bulgaricus* has specifically been investigated for fermentation of *T. diversifolia* because of its reported ability to reduce phytic acid concentrations [29].

Different microbial strains contribute distinct functional characteristics to fermentation. *L. plantarum* is capable of rapidly acidifying plant substrates under suitable conditions, thereby promoting preservation and limiting the growth of spoilage microorganisms [14]. Selection of an appropriate inoculant should therefore consider not only acidification capacity but also substrate compatibility, enzymatic activity, survival during fermentation, and the specific nutritional limitations targeted by processing.

Yeasts and filamentous fungi may also be incorporated into certain fermentation systems. These microorganisms can produce enzymes and fermentation metabolites that complement bacterial activity and facilitate the degradation of complex plant constituents [35]. However, the interactions among LAB, yeasts, and fungi depend strongly on microbial species, substrate composition, environmental conditions, and fermentation objectives. Their use in *T. diversifolia* therefore requires direct evaluation rather than extrapolation from fermented foods or unrelated feed substrates.

Fermentation duration is an important determinant of both nutrient preservation and anti-nutritional factor degradation. Fermentation of *T. diversifolia* with LAB has been evaluated over periods of approximately 2–5 days, during which changes in phytic acid and other fermentation characteristics have been observed. Fermentation with *L. bulgaricus* for 5 days has been reported to produce a substantial reduction in phytic acid under the experimental conditions evaluated [29]. Nevertheless, a 5-day period should not be regarded as universally optimal because fermentation responses depend on inoculum concentration, substrate characteristics, moisture content, temperature, and other interacting variables.

Fermentation duration should therefore be optimized together with inoculum dosage and environmental conditions. Studies using *L. bulgaricus* at different inoculation levels and fermentation periods have demonstrated changes in phytic acid concentration, enzymatic activity, and fermentation characteristics [29]. Experimental approaches such as factorial designs or response surface methodology may be useful for simultaneously evaluating fermentation time, inoculum concentration, temperature, moisture, and other processing variables rather than optimizing each factor independently [120].

Temperature strongly influences microbial growth and metabolic activity during fermentation. Many LAB used in feed fermentation perform effectively within temperatures of approximately 30°C–37°C, although optimal conditions differ among species and strains [14]. *A. ficuum* is also used in selected fermentation systems because of its enzyme-producing capacity, but its optimal growth conditions and functional role differ from those of LAB. Therefore, temperature requirements should be established for the specific microbial culture or consortium being used rather than assuming a common optimum for bacteria and fungi.

In tropical production environments, ambient temperatures may fall within ranges favorable for selected fermentation microorganisms, potentially reducing the requirement for external heating. However, high or fluctuating temperatures can also affect fermentation kinetics, nutrient losses, microbial succession, and spoilage risk. Temperature should therefore be monitored alongside other fermentation indicators, particularly when processing is conducted under farm conditions.

Acidification is an important indicator of successful LAB fermentation. Production of lactic and other organic acids lowers substrate pH, thereby suppressing many undesirable microorganisms and improving preservation [118]. A final pH below approximately 4.5 is often associated with stable fermentation in many ensiled feed materials; however, the appropriate terminal pH depends on substrate DM content, buffering capacity, sugar

availability, microbial populations, and fermentation system. Consequently, pH should not be used as the sole criterion of fermentation quality.

Assessment of fermentation success should also include nutrient retention, concentrations of anti-nutritional compounds, organic acid profiles, microbial counts, DM losses, and hygienic quality. In *T. diversifolia*, LAB fermentation can reduce phytic acid concentrations and modify other components that influence feeding value [14]. Nevertheless, improvements in chemical composition should be evaluated together with nutrient digestibility and animal responses before nutritional benefits are inferred.

Fermentation can occur under aerobic or anaerobic conditions depending on the microorganism and processing objective. LAB used for forage preservation generally perform most effectively when oxygen exposure is minimized, because anaerobic conditions favor desirable acid fermentation while limiting aerobic spoilage microorganisms [90]. Sealing *T. diversifolia* during fermentation can therefore help establish conditions conducive to forage preservation and controlled microbial activity.

Storage stability is equally important because fermentation quality can change after the active fermentation phase. Storage duration and oxygen exposure may influence pH, nutrient composition, microbial populations, and metabolite profiles [86]. Consequently, evaluations of fermented *T. diversifolia* should include not only immediate fermentation characteristics but also shelf life and aerobic stability after opening or exposure to air.

Fermentation may improve the palatability and nutritional characteristics of *T. diversifolia* under suitable processing conditions [14, 70]. Reductions in phytic acid and excessive tannin concentrations may increase the potential availability of minerals and proteins [29]. However, the presence of viable LAB in fermented forage should not automatically be interpreted as providing probiotic effects because survival through the gastrointestinal tract and demonstrable benefits to the host must be established experimentally [109].

Sensory characteristics and voluntary intake should also be considered when evaluating processed forage. Fermentation can alter odor, taste, texture, and other physical characteristics that influence feed acceptance [121]. Palatability measurements can therefore complement chemical and microbiological assessments of fermentation quality. At the farm level, practical adoption also depends on labor requirements, equipment, availability and cost of inoculants, storage capacity, processing losses, and technical knowledge. Haymaking and ensiling may provide practical preservation options for smallholders when technologies are adapted to local resources and climatic conditions [114].

The evidence discussed in this section should be interpreted according to the substrate and experimental conditions used in each study. Findings obtained directly from *T. diversifolia* provide the primary basis for evaluating its fermentation responses, whereas studies conducted with other feed materials are considered only as complementary mechanistic evidence. Results from different substrates should not be assumed to produce identical responses in *T. diversifolia*, because fermentation outcomes are influenced by microorganism or strain, inoculum concentration, moisture content, fermentation duration, temperature, substrate composition, and other environmental conditions. Accordingly, mechanistic information from other substrates is used to provide contextual support rather than direct evidence of fermentation effects in *T. diversifolia*.

OPTIMIZING CONDITIONS FOR MAXIMUM NUTRIENT RETENTION

Optimization of fermentation conditions is essential for preserving desirable nutrients while reducing anti-nutritional compounds in *T. diversifolia*. Appropriate microbial strains, fermentation duration, temperature, pH, moisture, oxygen exposure, and inoculum concentration interact to determine fermentation quality. Optimization should therefore focus on achieving an appropriate balance between substrate preservation, anti-nutritional factor reduction, nutrient retention, hygienic quality, and practical feasibility.

LAB, including *L. bulgaricus* and *L. plantarum*, have been investigated as microbial inoculants for processing *T. diversifolia* because of their acid-producing activity and potential effects on anti-nutritional compounds [14]. Pazla *et al.* [51] reported that fermentation involving 3% *L. bulgaricus*, with the microbial culture incubated at 37°C for 5 days, was associated with favorable subsequent rumen fermentation characteristics, including a ruminal pH of approximately 6.84. Importantly, this ruminal pH value reflects fermentation within the rumen after feeding or experimental incubation and should not be confused with the pH of the fermented forage itself.

LAB-mediated degradation of phytic acid may improve the potential availability of phosphorus and minerals bound within phytate complexes [29]. *L. plantarum* is particularly useful in feed fermentation because it can grow on a variety of plant substrates and rapidly produce organic acids under suitable conditions [122]. Nevertheless, inoculation with LAB does not by itself guarantee a nutritionally superior product; fermentation performance

depends on substrate fermentability, initial microbial populations, environmental conditions, and the capacity of the selected strain to dominate the fermentation process.

Fungal cultures may complement LAB by providing extracellular enzymes capable of degrading complex plant constituents. *Aspergillus oryzae* and *A. ficuum* have been investigated in fermentation systems for their enzyme-producing capacities. *A. ficuum*, in particular, can produce phytase, which hydrolyzes phytic acid and may increase the potential availability of phosphorus and calcium [82]. Combining bacterial and fungal cultures could therefore provide complementary enzymatic activities, but claims of synergistic effects require direct comparative evidence in *T. diversifolia*.

Fermentation duration must be sufficient to promote desirable microbial activity and reduce selected anti-nutritional compounds without causing excessive nutrient losses. Pazla *et al.* [14] reported reductions in anti-nutritional factors following fermentation of plant-based feed materials. In *T. diversifolia*, fermentation periods of approximately 5 days have been associated with substantial reductions in phytic acid and favorable changes in nutritional characteristics under selected experimental conditions [9, 14, 51]. However, the optimal duration should be determined for each processing system rather than assumed to be identical across substrates and microbial inoculants.

Excessively prolonged fermentation may increase DM losses, proteolysis, or degradation of fermentable nutrients. Optimization should therefore consider nutrient retention together with anti-nutritional factor reduction. Measurements of DM recovery, protein fractions, fiber composition, organic acids, ammonia nitrogen, microbial populations, and anti-nutritional compounds would provide a more comprehensive assessment of processing efficiency than fermentation duration alone.

Temperature must also be adapted to the microorganisms used. Many LAB strains perform effectively at approximately 30°C–37°C, although optimum temperatures vary among cultures. Ahn *et al.* [123] demonstrated that temperature strongly influences LAB metabolic activity and acid production. Tropical ambient conditions may therefore be suitable for fermentation of *T. diversifolia* in some environments, although fluctuations outside the optimal range could adversely affect fermentation consistency and preservation.

Control of substrate pH is important because rapid acidification suppresses undesirable microorganisms and supports preservation. Poppe *et al.* [120] emphasized the importance of pH as one component of fermentation control. For *T. diversifolia*, achieving sufficiently rapid acidification may contribute to fermentation stability; however, a universal target of pH 4.5 cannot be considered optimal under all conditions because final pH is influenced by DM concentration, buffering capacity, fermentable carbohydrate supply, and the fermentation system.

Minimizing oxygen exposure during fermentation is generally desirable for LAB-dominated forage preservation. Anaerobic conditions reduce oxidative losses and restrict the proliferation of many aerobic spoilage microorganisms [14]. Appropriate compaction and sealing can therefore improve fermentation stability. However, aerobic stability after opening is also important because fermented material may deteriorate rapidly when exposed to oxygen, particularly if yeasts and molds proliferate.

Optimized fermentation may improve the potential availability of selected nutrients. Suvarna *et al.* [99] demonstrated reductions in phytic acid following LAB fermentation of linseed, with corresponding implications for mineral availability. Similar reductions in phytic acid have been reported in fermented *T. diversifolia*, together with changes in tannin and oxalate concentrations [124]. However, findings from other substrates should be regarded as supportive mechanistic evidence rather than direct proof of identical responses in *T. diversifolia*.

Fermentation may also modify protein fractions and improve the accessibility of dietary protein under appropriate conditions. Such changes could contribute to nutrient utilization in ruminants, but improved chemical accessibility does not necessarily translate directly into greater protein absorption, growth, or milk production [50]. Similarly, potential probiotic effects of residual LAB in fermented *T. diversifolia* require confirmation through studies demonstrating microbial viability, gastrointestinal persistence, and measurable host benefits [109].

Future optimization of *T. diversifolia* processing should integrate microbial strain selection, inoculum concentration, fermentation duration, temperature, moisture, substrate composition, additives, and storage conditions within a unified experimental framework. Approaches such as microbial consortia, SSF, and enzyme supplementation with phytase or fibrolytic enzymes may offer additional opportunities to improve anti-nutritional factor degradation and nutrient utilization [103-105, 117, 124, 125]. Biochar-assisted fermentation has also been proposed as an emerging approach; however, its application to *T. diversifolia* remains insufficiently characterized. Before these technologies are recommended commercially, their effects on nutrient retention,

fermentation stability, palatability, animal performance, economic feasibility, scale-up, and potential residual or undesirable fermentation products should be evaluated through controlled *in vivo* and farm-scale studies.

ENSILING WITH *T. diversifolia* AND OTHER FORAGES

Ensiling *T. diversifolia* with complementary forage resources offers a potential strategy for producing nutritionally balanced and storable ruminant feed. Combining protein-rich *T. diversifolia* with carbohydrate-rich or fibrous materials can improve substrate characteristics for fermentation while broadening the nutrient profile of the resulting silage. The effectiveness of mixed silage, however, depends on the proportions of individual ingredients, fermentable carbohydrate supply, moisture content, buffering capacity, microbial activity, and ensiling management.

T. diversifolia contains relatively high concentrations of protein and minerals, whereas complementary forages may supply greater amounts of fermentable carbohydrates or structural fiber [74]. When combined with *P. purpureum*, the resulting mixture may provide a more balanced energy-to-protein supply than either forage alone, depending on their respective proportions and maturity [57]. Such combinations can potentially improve the nutritional characteristics of the silage, although their effects on animal performance must be demonstrated through feeding trials rather than inferred solely from chemical composition.

Ensiling modifies plant material through microbial fermentation and acidification, which can alter structural carbohydrates and selected anti-nutritional compounds. Inclusion of *T. diversifolia* in mixed silages has been associated with favorable changes in nutrient composition and digestibility under some experimental conditions [9]. However, improved fiber utilization should not automatically be attributed to a synergistic interaction among forage components because digestibility responses depend on the characteristics of the individual ingredients, fermentation quality, and composition of the complete diet.

The inclusion of sugar-rich plant materials, such as sugarcane shoots, can increase the supply of water-soluble carbohydrates available to LAB. Adequate fermentable carbohydrate availability supports rapid acid production, promotes pH decline, and can improve silage preservation [126]. These effects may enhance fermentation quality, but improved palatability and voluntary intake should be confirmed directly because sensory responses depend on acid concentrations, fermentation end products, moisture content, and the physical characteristics of the final silage.

Mixed-forage ensiling also creates a more complex fermentation substrate that may support diverse microbial populations. However, greater microbial diversity is not necessarily synonymous with superior fermentation quality. Inoculation with selected LAB, including *L. bulgaricus*, may promote desirable acidification under appropriate conditions [51]. The principal fermentation products of LAB are organic acids, particularly lactic acid; VFAs detected in silage can also contribute to the fermentation profile, but their concentrations and significance depend on microbial pathways and fermentation quality.

Combining *T. diversifolia* with locally available plant materials may also improve resource-use efficiency by converting seasonally abundant forage or plant residues into preserved feed. *T. diversifolia* can contribute to soil nutrient cycling when its biomass is returned to the soil as green manure [54, 119]. However, it should not be described as a nitrogen-fixing plant because it does not biologically fix atmospheric nitrogen. Its agronomic value instead relates to rapid biomass production and the return of nutrients accumulated in its tissues.

Selection of complementary ingredients is critical for producing nutritionally and fermentatively suitable silage. *T. diversifolia* can contribute protein and minerals, whereas sugarcane shoots may provide readily fermentable carbohydrates [74]. Avocado leaves or other fibrous plant materials may alter the structural carbohydrate content of the mixture, but their inclusion should be evaluated carefully for nutrient composition, palatability, digestibility, and safety rather than assumed to improve the ration automatically [82].

Silage preparation generally involves chopping and thoroughly mixing the forage ingredients to promote compaction and uniform fermentation. LAB inoculation can be used to promote rapid acidification, although inoculation is not necessarily essential when sufficient indigenous LAB and fermentable carbohydrates are present. *L. bulgaricus* has also been investigated for its ability to reduce phytic acid in *T. diversifolia* [14, 29]. Proper compaction, exclusion of oxygen, and effective sealing remain fundamental to successful preservation.

Maintaining anaerobic conditions limits aerobic spoilage and favors desirable fermentation. This can be achieved through adequate compaction and airtight storage in silos, bags, or other suitable containers [126]. Temperature also influences microbial activity, although a single optimal temperature range cannot be applied universally because responses vary among microorganisms and substrates. Tropical environmental conditions

may be compatible with forage fermentation, but excessive temperatures can increase nutrient losses and undesirable microbial activity [57].

Monitoring silage quality should extend beyond pH alone. A sufficiently rapid decline in pH is desirable, but the final target varies according to forage DM concentration, buffering capacity, carbohydrate availability, and microbial population. Silage evaluation should therefore include DM recovery, organic acid composition, ammonia nitrogen, microbial quality, nutrient composition, aerobic stability, and concentrations of anti-nutritional compounds where relevant [9].

Feeding studies using combinations of *T. diversifolia* with other forage resources have reported favorable responses in DM intake, nutrient digestibility, and body weight gain under selected conditions [58]. These findings indicate that mixed silages may have practical value in ruminant production. Nevertheless, the observed responses should be interpreted in relation to ingredient proportions, basal diet composition, animal species, physiological status, and feeding duration.

Mixed silage may also influence ruminal fermentation after ingestion, including VFA production, which contributes substantially to the energy metabolism of ruminants. However, VFAs produced during ruminal fermentation should be distinguished from fermentation acids produced during ensiling. The economic value of mixed *T. diversifolia* silage will ultimately depend on forage availability, processing costs, storage losses, labor, animal responses, and the extent to which conventional or purchased feeds can be replaced [113].

FUTURE DIRECTIONS IN FERMENTATION RESEARCH

Future research on *T. diversifolia* processing should move beyond conventional single-strain fermentation toward more precisely controlled microbial, enzymatic, and pre-harvest nutritional strategies. Advances in microbial inoculants, enzyme supplementation, fermentation optimization, and plant-microbe interactions may improve preservation quality, nutrient availability, and reduction of anti-nutritional compounds. However, these technologies require direct validation in *T. diversifolia* before practical recommendations can be established.

LAB, including *L. plantarum* and *L. bulgaricus*, remain important inoculants because of their ability to rapidly acidify fermentable substrates and suppress many undesirable microorganisms. Studies indicate that LAB fermentation can reduce selected anti-nutritional compounds, including phytic acid and tannins, and thereby modify the nutritional characteristics of fermented feeds [127]. In *T. diversifolia*, microbial fermentation has also been associated with reductions in anti-nutritional factors and potential improvements in nutrient availability [82]. Nevertheless, the extent of these effects varies with strain, inoculum concentration, fermentation duration, substrate composition, and environmental conditions.

Microorganisms beyond conventional LAB are also being investigated for feed processing applications. Species belonging to *Bacillus* and *Pseudomonas* possess diverse metabolic and enzymatic capabilities that may influence nutrient transformation in plant substrates. However, their roles in *T. diversifolia* silage remain insufficiently characterized, and their suitability must be assessed at the species and strain levels because microorganisms within the same genus can differ substantially in metabolic activity, safety, and fermentation behavior. Controlled studies are therefore required before these organisms can be recommended as silage inoculants.

Exogenous enzymes, including cellulases, amylases, proteases, phytases, and other fibrolytic enzymes, may provide additional opportunities to modify plant structural components and improve nutrient accessibility. Campana *et al.* [125] reported that enzyme treatments can enhance nutrient release from fibrous feed materials. In *T. diversifolia*, such approaches could potentially complement microbial fermentation by targeting fiber fractions or anti-nutritional compounds; however, responses should be assessed through direct measurements of nutrient preservation, digestibility, and animal performance.

Phytase supplementation is particularly relevant because of the phytic acid content of *T. diversifolia*. Microbial phytase can hydrolyze phytate and potentially release bound phosphorus and other minerals [58]. Nevertheless, phytase production is not a universal characteristic of all LAB strains, and the effectiveness of phytase-mediated processing depends on enzyme activity, substrate pH, temperature, fermentation duration, and phytate concentration. Improvements in mineral bioavailability should therefore be confirmed through *in vivo* measurements rather than inferred solely from reductions in phytic acid [57].

Biofortification should be distinguished from post-harvest silage treatment. In its conventional sense, biofortification involves increasing the nutrient concentration of plants before harvest through genetic, agronomic, or biological approaches. Therefore, manipulation of soil fertility, beneficial rhizosphere micro-

organisms, or plant nutrient uptake represents a more appropriate biofortification strategy than simply adding fermentation additives during ensiling.

The use of biochar should likewise be evaluated according to its specific application. Incorporating biochar into soil may influence soil OM dynamics, nutrient retention, microbial communities, and subsequent plant growth [128]. However, evidence that adding biochar directly during silage preparation improves the nutrient density of *T. diversifolia* silage remains insufficient. Future studies should clearly distinguish soil-applied biochar effects from any proposed direct role of biochar as a fermentation additive.

Plant–microbe interactions represent another promising area of research. Rhizosphere microorganisms can influence nutrient cycling, plant nutrient acquisition, and tolerance to environmental stress. Wen *et al.* [129] highlighted the importance of rhizosphere microbial communities in nutrient availability and plant resilience. Manipulating beneficial plant-associated microorganisms could therefore provide a pre-harvest strategy for improving biomass production or nutrient accumulation in *T. diversifolia*, although the magnitude and consistency of these effects require field validation.

Future studies should integrate pre-harvest and post-harvest approaches rather than evaluating them independently. Research priorities include screening microbial strains and enzyme combinations, optimizing inoculum concentrations, determining fermentation kinetics, characterizing metabolite profiles, evaluating aerobic stability, and quantifying changes in anti-nutritional compounds and nutrient fractions. These laboratory measurements should subsequently be linked with *in vivo* assessments of intake, nutrient digestibility, rumen fermentation, animal performance, health indicators, methane emissions, and product quality.

Economic feasibility and farm-scale applicability should also be incorporated into future research. Novel inoculants, enzymes, microbial consortia, and biofortification strategies may improve processing efficiency under experimental conditions but remain impractical if they require expensive inputs, specialized equipment, or tightly controlled environmental conditions. Consequently, future technological development should balance biological effectiveness with cost, safety, storage stability, simplicity of application, and suitability for tropical smallholder production systems.

ROLE OF *T. diversifolia* IN SUSTAINABLE AGRICULTURE

Integration of *T. diversifolia* into crop–livestock systems may provide several agronomic and environmental benefits because of its adaptability, rapid biomass production, and potential contribution to nutrient recycling when biomass is deliberately returned to the soil. These characteristics make the species particularly relevant to tropical and resource-constrained agricultural systems in which locally available multipurpose plants can contribute simultaneously to forage production and soil management.

T. diversifolia can contribute to soil fertility through the production and decomposition of nutrient-rich biomass. When used as green manure or mulch, its residues return nitrogen and other nutrients to the soil during decomposition, which may contribute to nutrient supply and potentially reducing part of the requirement for external fertilizer inputs under appropriate management conditions [130]. However, *T. diversifolia* is not a nitrogen-fixing species and does not biologically fix atmospheric nitrogen. Its contribution to soil nitrogen therefore results primarily from nutrient uptake, biomass accumulation, and subsequent nutrient recycling. This characteristic is consistent with sustainable agricultural approaches that aim to improve internal nutrient cycling and reduce unnecessary dependence on external inputs [131].

The ability of *T. diversifolia* to persist under periods of limited water availability may further increase its value in tropical forage systems. Its root system can enable access to water and nutrients from deeper soil layers, contributing to persistence during dry periods [78]. Nevertheless, its drought tolerance should not be interpreted as complete resistance to water stress, because biomass production and forage quality may still decline under prolonged or severe drought. Its relative resilience may, however, help maintain forage availability during periods when more water-sensitive species become less productive.

T. diversifolia is also capable of growing across a range of soil conditions, including acidic and relatively nutrient-poor soils. This adaptability may allow its cultivation on land that is less suitable for more demanding forage crops. Its root system and aboveground biomass can contribute to soil cover and stabilization, potentially reducing erosion where the plant is appropriately managed [132]. In addition, *T. diversifolia* has been reported to acquire phosphorus efficiently from soils with low phosphorus availability, [30]. When its biomass is subsequently returned to the soil through green-manure or mulch applications, decomposition can contribute to the release and recycling of phosphorus. However, these processes should not be interpreted as evidence of improved soil

fertility across all production systems, as their effects depend on soil properties, biomass management, and nutrient dynamics.

The species may also be incorporated into agroforestry and silvopastoral systems because of its multifunctional characteristics. When established as hedgerows, boundary vegetation, forage banks, or biomass sources, *T. diversifolia* can contribute to diversified land use and when biomass is returned to the soil, nutrient cycling [133, 134]. Its flowering may also provide resources for some pollinators, while its litter and root-associated processes can influence soil biological activity. However, claims of enhanced biodiversity should be evaluated in relation to local management because *T. diversifolia* can display invasive behavior in some environments. Controlled establishment and prevention of unintended spread are therefore important when integrating the species into diversified production systems.

Use of *T. diversifolia* as green manure or mulch can contribute substantial organic biomass to soil. Decomposition releases nutrients, including nitrogen, phosphorus, and potassium, which can subsequently become available for plant uptake [130]. Organic amendments derived from *T. diversifolia* may also influence microbial activity and soil biological processes. Nevertheless, the magnitude and duration of these effects depend on biomass quantity and composition, soil characteristics, decomposition rate, climatic conditions, and interactions with other nutrient management practices.

The physical presence of *T. diversifolia* can also contribute to erosion management by increasing vegetative cover and reducing direct rainfall impact on exposed soil. Where planted appropriately on slopes or erosion-prone areas, its root system and surface biomass may reduce runoff and soil loss [73]. These effects are likely to be most effective when *T. diversifolia* is incorporated within broader soil-conservation strategies rather than used as a stand-alone measure.

Addition of *T. diversifolia* biomass as green manure or mulch can further increase the input of OM to soil. Repeated applications of *T. diversifolia* biomass as organic amendments may contribute to improved soil structure, water-holding capacity, nutrient retention, and biological activity [82]. They may also contribute to soil organic carbon accumulation under favorable conditions. However, the extent to which *T. diversifolia* increases long-term carbon sequestration depends on biomass production, decomposition rates, soil properties, management intensity, and the persistence of added carbon. Consequently, carbon sequestration benefits should be quantified directly rather than inferred solely from biomass incorporation.

Overall, the agronomic value of *T. diversifolia* lies in its ability to combine forage production with potential nutrient recycling when biomass is appropriately managed and returned to the soil, biomass generation, soil cover, and potential integration into agroforestry or silvopastoral systems. These functions may improve resource-use efficiency in tropical livestock production, particularly when the species is managed as part of an integrated farming system. However, site-specific evaluation is necessary to balance productivity, soil benefits, water use, labor requirements, and ecological risks associated with uncontrolled spread.

COST-EFFECTIVENESS AND ECONOMIC IMPACT FOR FARMERS

The incorporation of *T. diversifolia* into livestock feeding systems may provide economic advantages where the plant is locally available and can partially replace purchased forage, concentrates, or other conventional feed ingredients. Potential savings are particularly relevant to smallholder farmers exposed to high feed prices, seasonal forage shortages, and transportation costs. However, the economic value of *T. diversifolia* depends on production, harvesting, processing, storage, labor, and animal performance responses and should therefore be assessed at the whole-farm level.

One potential advantage is the ability of *T. diversifolia* to produce substantial biomass under relatively low-input conditions. Its nutrient-rich biomass may also be used in soil fertility management, potentially complementing mineral fertilizers rather than replacing them entirely. Muthuri *et al.* [73] reported beneficial responses when *T. diversifolia* biomass was integrated with mineral fertilizer management. Such combined approaches may improve nutrient-use efficiency and crop productivity, but the degree of fertilizer saving and associated economic benefit will vary according to soil fertility, crop requirements, biomass availability, labor, and fertilizer prices.

The adaptability of *T. diversifolia* to diverse environmental conditions may facilitate local forage production, including in some low-fertility areas. Local cultivation can potentially reduce dependence on externally purchased feeds and associated transportation costs, particularly in remote production systems. Nevertheless, accessibility does not necessarily imply negligible production cost. Land allocation, establishment, harvesting frequency, labor,

transport within the farm, and competition with other land uses should all be incorporated into economic assessments.

Labor requirements represent an important component of the economics of *T. diversifolia* utilization. Harvesting, chopping, transporting, fermenting, ensiling, and feeding the biomass can require substantial manual input. Ntakyo *et al.* [114] emphasized the importance of considering labor and preservation costs when evaluating forage technologies in smallholder systems. Therefore, the economic advantage of *T. diversifolia* is likely to depend on whether the value of improved forage availability and livestock performance offsets these additional processing and labor requirements.

Productive responses can also influence economic returns. Jamarun *et al.* [135] reported favorable growth and feed-utilization responses when fermented *T. diversifolia* was incorporated with other dietary ingredients in goats. Such responses suggest that properly formulated diets containing *T. diversifolia* may improve the efficiency of locally available feed resources. However, improvements in feed efficiency should not be generalized across production systems because responses vary with inclusion level, basal diet, processing method, animal species, and physiological status.

The nutritional characteristics of *T. diversifolia*, particularly its relatively high CP and mineral concentrations, may allow it to contribute to dietary protein and mineral supply and thereby reduce dependence on some purchased ingredients. Cadena-Villegas *et al.* [67] reported favorable nutritional and productive responses associated with its inclusion in ruminant diets. Nevertheless, improved nutritional status should not be interpreted as a guaranteed increase in growth, milk yield, reproductive performance, or health because these outcomes depend on the balance of the entire diet and overall herd management.

Economic benefits may also arise indirectly through greater resilience of integrated crop–livestock systems. Locally produced forage can reduce exposure to fluctuations in commercial feed prices and interruptions in external supply chains. In addition, the use of *T. diversifolia* biomass for both animal feeding and soil nutrient recycling may create complementarities between livestock and crop enterprises. Such integration can improve internal resource cycling and potentially reduce waste, although the magnitude of the financial benefit requires farm-specific assessment.

The environmental functions of *T. diversifolia* may further contribute to long-term economic resilience, particularly where soil degradation, erosion, or declining fertility constrain agricultural productivity. Improved soil cover, OM inputs, and nutrient recycling may help maintain productive capacity over time. However, these ecosystem services are difficult to translate directly into short-term monetary returns and should be evaluated alongside immediate costs and livestock outputs.

Future economic assessments should therefore move beyond simple comparisons of feed purchase prices. Comprehensive analyses should include establishment costs, land requirements, biomass yield, harvesting and processing labor, ensiling or fermentation expenses, storage losses, transportation, seasonal availability, animal performance, product value, and potential agronomic co-benefits. Cost–benefit analysis, partial budgeting, and whole-farm economic modeling would provide a more reliable basis for determining where *T. diversifolia* offers a genuine financial advantage to smallholder livestock producers.

CONTRIBUTION TO CLIMATE CHANGE MITIGATION

The integration of *T. diversifolia* into ruminant feeding and mixed farming systems may contribute to climate change mitigation through two principal pathways: modification of enteric methane production and improved management of soil OM and carbon. These potential benefits are consistent with broader efforts to reduce agricultural GHG emissions and improve land use sustainability. The environmental factors summarized in Table 6 [12, 73, 80, 136-139] provide context for evaluating the contribution of *T. diversifolia* within livestock production systems.

The environmental effects summarized in Table 6 are not exclusive to *T. diversifolia*, but they are relevant to understanding its performance within tropical livestock and agroforestry systems. Its overall contribution to climate mitigation depends not only on forage composition and methane-mitigating potential but also on management factors such as grazing intensity, grazing exclusion, climatic conditions, altitude, biomass production, and integration within agroforestry or silvopastoral systems. These factors can influence forage productivity, ecosystem services, soil carbon dynamics, and the net environmental performance of the production system.

Enteric methane represents an important component of GHG emissions from ruminant production. Dietary inclusion of *T. diversifolia* has been associated with reductions in methane emissions under certain experimental

conditions, largely because of its secondary metabolites and their effects on ruminal fermentation. However, the magnitude of the response varies according to inclusion level, basal diet, animal type, and experimental design.

Table 6: Environmental factors and management strategies influencing greenhouse gas emissions and climate change dynamics.

Environmental factor/strategy	Effect observed	Reference
Grazing intensity	Light grazing decreases GWP, whereas heavy grazing increases GWP	[79, 136]
Climate change	Alters habitat distribution and may increase the invasive potential of species such as <i>Tithonia diversifolia</i>	[12, 80]
Grazing exclusion	Reduces GWP but may increase CH ₄ emissions over time, depending on the duration of exclusion	[80, 136]
Carbon sequestration in agroforestry	Agroforestry systems can store carbon in biomass and soil, thereby contributing to climate change mitigation	[73, 137–139]
Altitudinal gradient	Higher altitudes are associated with increased GHG emissions under grazing conditions	[80, 136]

GHG = greenhouse gas; GWP = global warming potential.

The methane-mitigating effects of *T. diversifolia* have been associated particularly with tannins and saponins, which can alter rumen microbial populations and hydrogen utilization. These compounds may reduce protozoal activity and modify interactions involving methanogenic archaea, thereby decreasing the availability of hydrogen for methanogenesis. Rivera *et al.* [76] reported a reduction of up to 6.8% in methane emissions when *T. diversifolia* was included at 15% of the diet in dairy cows. These findings support its potential as a methane-mitigating forage, although the response should not be generalized across production systems without considering dietary and management differences.

Pazla *et al.* [51] also reported favorable rumen fermentation responses after processing *T. diversifolia* with *L. bulgaricus*. Fermentation may modify nutrient availability and the composition of anti-nutritional compounds, which can subsequently influence ruminal digestion and fermentation patterns. Nevertheless, improvements in digestibility or fermentation characteristics should not automatically be interpreted as direct reductions in methane emissions unless methane is measured explicitly. Further *in vivo* studies are therefore needed to determine whether fermentation processing consistently enhances the methane-mitigating effect of *T. diversifolia*.

Beyond enteric methane, *T. diversifolia* may contribute indirectly to soil carbon management through biomass production and incorporation into soil. When used as green manure, mulch, or an agroforestry biomass resource, its residues add organic material that can influence soil OM, nutrient cycling, and microbial activity. However, *T. diversifolia* is not a nitrogen-fixing species; its contribution to soil fertility results from nutrient uptake, biomass accumulation, and subsequent nutrient recycling rather than biological fixation of atmospheric nitrogen.

Incorporation of *T. diversifolia* biomass into soil may contribute to soil organic carbon inputs and improve selected soil properties. Its relatively rapid biomass production can provide substantial quantities of organic residues, and annual biomass yields of up to approximately 8 t/ha have been reported under some conditions. Decomposition of this biomass can enhance microbial activity and nutrient release. Nevertheless, greater OM input does not necessarily result in equivalent long-term carbon sequestration because a substantial proportion of added carbon may be mineralized and returned to the atmosphere. Long-term changes in soil carbon stocks therefore require direct field measurement.

The integration of *T. diversifolia* into agroforestry and silvopastoral systems may provide additional opportunities for carbon storage because such systems combine forage, shrubs, and trees with different rooting depths and biomass pools. The contribution of *T. diversifolia* itself is likely to be greatest through rapid biomass turnover, ground cover, and nutrient recycling, whereas much of the long-term carbon storage in agroforestry systems may be associated with perennial woody biomass and stable soil carbon pools. Consequently, the carbon sequestration contribution of *T. diversifolia* should be evaluated as part of the complete production system rather than in isolation.

The use of *T. diversifolia* may also contribute to reduced dependence on externally sourced feed and fertilizer inputs in integrated crop–livestock systems. Such reductions could potentially lower upstream emissions associated with feed production, fertilizer manufacture, and transportation. However, these benefits are system-specific and require life cycle or whole-farm assessment to determine whether net GHG emissions are actually reduced.

Integration of *T. diversifolia* into climate-smart livestock systems is therefore best considered as a

complementary mitigation strategy rather than a stand-alone solution. Its nutritional value, potential methane-mitigating effects, biomass production, and role in nutrient cycling may together improve the environmental efficiency of tropical livestock systems. However, its contribution to climate objectives should be quantified using direct measurements of enteric methane, soil carbon changes, land use effects, fertilizer substitution, animal productivity, and whole-farm GHG emissions rather than inferred from individual plant characteristics alone.

BIODIVERSITY AND AGROFORESTRY APPLICATIONS

Integration of *T. diversifolia* into agroforestry and silvopastoral systems may contribute to diversified land use, soil protection, nutrient cycling, and habitat provision. These functions are particularly relevant in tropical and subtropical production systems where maintaining soil fertility and ecological resilience is important for long-term agricultural sustainability. However, biodiversity benefits depend strongly on local management because *T. diversifolia* can also behave invasively if its spread is not controlled.

When used as green manure, mulch, hedgerows, or biomass strips, *T. diversifolia* can contribute nutrient-rich organic material to the soil. Its tissues contain appreciable amounts of nitrogen and phosphorus, and decomposition can release these nutrients and increase OM inputs [140]. Ramadhani *et al.* [140] reported improvements in soil-related properties within diversified agroforestry systems involving nutrient-rich plant biomass. These effects can support nutrient cycling and soil biological activity, although the contribution of *T. diversifolia* should be distinguished from the combined effects of the entire agroforestry system.

Its root system and aboveground cover may also contribute to soil stabilization in erosion-prone environments. Establishment on slopes or along contour lines can reduce exposed soil surface and help limit runoff and soil displacement. Rois-Díaz *et al.* [141] emphasized the importance of perennial vegetation and agroforestry structures in reducing erosion risk. The effectiveness of *T. diversifolia* for erosion control will nevertheless depend on planting density, slope, rainfall intensity, soil type, and integration with other conservation practices.

Agroforestry systems generally support greater structural and botanical diversity than monocultures, thereby providing a wider range of habitats and food resources for organisms. Where *T. diversifolia* is incorporated appropriately, its flowers, foliage, and associated vegetation may contribute to habitat complexity. Muthuri *et al.* [73] described the biodiversity value of diversified agroforestry systems in East Africa, although the biodiversity effects should not be attributed solely to *T. diversifolia*.

The flowers of *T. diversifolia* may provide nectar and pollen resources for insect visitors, including bees. In diversified agroforestry landscapes, flowering plant diversity can support pollinator abundance and continuity of floral resources. Islam *et al.* [142] reported positive relationships between plant diversity and ecosystem functions in agroforestry systems. However, increased pollinator visitation should not automatically be interpreted as greater crop yield without crop-specific evidence.

Soil microbial communities may also respond to the presence of diverse plant species and organic inputs. Litter deposition, root exudates, and biomass incorporation can influence microbial activity and nutrient transformations. Islam *et al.* [142] highlighted the importance of biological diversity in agroforestry soils. Nevertheless, claims that *T. diversifolia* directly suppresses soil-borne diseases require specific experimental evidence and should not be inferred from microbial diversity alone.

Agroforestry systems that combine species with contrasting growth forms and rooting patterns can improve the temporal and spatial use of light, water, and nutrients. Rahman *et al.* [143] reported improved resource-use efficiency in diversified land use systems compared with simpler production systems. *T. diversifolia* may contribute to such systems as a rapidly growing shrub used for forage, biomass, or boundary planting, but whether it increases total productivity depends on competition, shading, water availability, and management intensity.

Agroforestry systems can also store more carbon than annual monocultures because they contain greater perennial biomass and may increase soil carbon inputs. *T. diversifolia* can contribute through aboveground biomass, root turnover, litter deposition, and organic residue incorporation [53]. Lehmann *et al.* [144] emphasized the importance of diversified perennial systems for carbon storage. However, *T. diversifolia* should not be described as an independent long-term carbon sink without direct evidence of persistent carbon accumulation attributable specifically to the species.

Within livestock-oriented agroforestry systems, *T. diversifolia* can provide a protein- and mineral-rich supplementary forage [135, 145]. Its adaptability and rapid biomass production may make it useful as a forage bank or cut-and-carry resource. Combinations with locally available feeds, including avocado leaves, may broaden

the nutrient profile of the ration [82]. Nevertheless, dietary combinations should be evaluated for nutritional balance, palatability, anti-nutritional compounds, and safety rather than assumed to produce an inherently balanced diet.

The biodiversity value of *T. diversifolia* must also be considered alongside its potential invasiveness. Uncontrolled establishment can alter native plant communities and compete with other vegetation. Therefore, its use in agroforestry should include appropriate containment, harvesting, reproductive management, and monitoring of spread. In this context, *T. diversifolia* is most appropriately regarded as a multifunctional managed species whose ecological benefits depend on deliberate integration within diverse production systems.

SEASONAL AVAILABILITY AND HARVESTING LIMITATIONS

T. diversifolia is a promising forage resource because of its adaptability, favorable nutrient composition, and capacity for substantial biomass production. However, seasonal variation in biomass availability, together with harvesting, preservation, and storage constraints, can limit its continuous use in ruminant feeding systems. These limitations are particularly relevant in tropical production environments where rainfall distribution strongly influences forage availability and quality.

Biomass production of *T. diversifolia* varies with rainfall, temperature, soil fertility, genotype, plant maturity and harvest management. Under adequate moisture and favorable growing conditions, biomass accumulation may increase, whereas prolonged dry periods can reduce growth and regrowth [146]. This seasonal production pattern can contribute to forage surpluses during the rainy season and shortages during the dry season, particularly in livestock systems that depend heavily on locally produced forage resources [147]. Consequently, reliance on *T. diversifolia* as a major feed source requires appropriate harvesting and conservation strategies to buffer seasonal fluctuations.

Seasonal variation in biomass availability can also influence livestock feeding programs. During periods of limited forage supply, reductions in both feed quantity and quality may constrain nutrient intake and animal performance. Appropriate management of cutting frequency, harvest maturity, regrowth intervals, and forage allocation can help synchronize biomass production with livestock requirements and reduce seasonal gaps in feed availability [30]. However, optimal harvesting schedules should be adapted to local rainfall patterns, soil fertility, plant maturity, and production objectives. Consequently, no single harvesting schedule can be considered universally optimal across production environments.

Preservation is therefore important for extending the use of *T. diversifolia* beyond the period of active growth. Without appropriate storage, harvested forage can undergo DM losses, nutrient degradation, undesirable microbial activity, and spoilage, thereby reducing its feeding value [148]. Conservation strategies should aim to retain nutrients while minimizing deterioration during storage.

Ensiling represents one of the most practical approaches for conserving *T. diversifolia* during periods of surplus production. Ensiling alone or in combination with complementary forage materials can preserve biomass for use during seasonal shortages while also modifying selected anti-nutritional compounds [149]. Mixed silages containing *T. diversifolia* and *P. purpureum* have been evaluated as a means of improving preservation and maintaining forage availability during dry periods [57]. Nevertheless, successful ensiling depends on forage moisture content, fermentable carbohydrate availability, compaction, exclusion of oxygen, and storage management.

Hermetic storage technologies may also have potential for preserving appropriately processed or dried feed materials. Purdue Improved Crop Storage (PICS) bags provide low-oxygen storage conditions and have been widely evaluated for the preservation of dry agricultural commodities. Irawan and Komori [150] discussed hermetic storage approaches under conditions in which conventional storage infrastructure is limited. However, the direct applicability of PICS bags to high-moisture *T. diversifolia* forage should not be assumed without specific evidence because fresh forage requires controlled fermentation or adequate drying to prevent deterioration. Similarly, controlled-atmosphere storage may reduce oxidative deterioration under suitable conditions [151], but its cost and technical requirements may limit practical application in smallholder forage systems.

For smallholder farmers, seasonal forage conservation has important economic implications. Strategic harvesting and storage of *T. diversifolia* during periods of high biomass production may reduce dependence on purchased feeds during seasonal shortages [152]. However, economic benefits depend on labor requirements, storage losses, chopping or drying costs, fermentation inputs, equipment, and the value of feeds displaced. Farm level economic evaluation is therefore necessary before assuming that forage conservation will consistently

reduce feeding costs.

Integration of *T. diversifolia* into agroforestry, silvopastoral, cut-and-carry, and rotational forage systems may further improve the resilience of seasonal feed supply. The performance of these systems may vary with genotype, climate, soil conditions, planting density, and management intensity. Appropriate integration can contribute to biomass production, soil cover, nutrient recycling, and erosion management [153]. Nevertheless, these benefits depend on planting density, harvesting intensity, competition with associated crops, and control of potential invasiveness. Combined with effective conservation strategies, these systems may help improve forage availability and strengthen the resilience of tropical livestock production [154, 155].

PALATABILITY AND ANIMAL ACCEPTANCE

Palatability influences voluntary feed intake and is determined by multiple sensory and physical characteristics, including taste, odor, texture, moisture, particle size, previous dietary experience, and associations formed by the animal after ingestion. In *T. diversifolia*, secondary metabolites such as tannins and saponins may influence sensory characteristics and feed acceptance, particularly at high dietary concentrations [9]. Phytic acid is nutritionally important because of its mineral binding properties, but it should not be regarded as a principal cause of bitterness or reduced palatability without specific sensory evidence.

The physical characteristics of *T. diversifolia* may also influence acceptance. Mature stems and coarse plant material can reduce ease of prehension and chewing, whereas physical processing through chopping or grinding may improve handling and facilitate consumption [92]. Particle size and moisture content can affect feed texture and feeding behavior, although excessively fine processing may also influence rumination and the physical effectiveness of fiber [157]. Processing should therefore seek an appropriate balance between ease of consumption and maintenance of desirable forage structure.

Novel feeds may initially be consumed cautiously because animals require time to become familiar with their sensory characteristics and post-ingestive effects. Gradual introduction of *T. diversifolia* together with familiar dietary ingredients may facilitate adaptation and improve acceptance [121]. This approach is particularly relevant where animals have had little previous exposure to the forage.

Blending *T. diversifolia* with complementary feeds is another practical strategy for improving dietary acceptance. Mixtures with sugarcane shoots, grasses, legumes, or other locally available feeds can alter flavor, texture, and nutrient composition and may make the complete ration more acceptable to livestock [50, 157]. However, greater intake should not automatically be attributed to masking bitterness because dietary balance, moisture, physical form, and energy density can also influence consumption.

Fermentation may further alter the sensory and nutritional characteristics of *T. diversifolia*. LAB fermentation with *L. bulgaricus* can reduce phytic acid and modify other plant constituents [158]. Fermentation also produces organic acids and other metabolites that alter feed aroma and taste. These changes may influence palatability, but fermentation does not invariably increase intake because excessively acidic, poorly fermented, or spoiled material can reduce acceptance. Therefore, palatability should be assessed directly through voluntary intake or preference measurements rather than inferred solely from changes in fermentation chemistry [74, 82].

Physical processing techniques such as grinding, pelleting, chopping, and ensiling may improve handling characteristics and facilitate consumption. Ensiling can soften plant tissues and modify texture through fermentation, whereas pelleting can produce a more uniform physical form and reduce selective feeding [149]. Nevertheless, the effect of these processes on voluntary intake depends on animal species, particle size, forage maturity, dietary composition, and processing severity.

Palatable additives such as molasses may also be incorporated into forage mixtures or silages to increase fermentable carbohydrate supply and improve sensory acceptance. Molasses can support desirable fermentation while contributing sweetness that may encourage intake [159]. The use of essential oils as flavor-modifying additives requires greater caution because some essential oils can affect rumen microorganisms and intake in a dose-dependent manner. Their inclusion should therefore be based on specific feeding evidence rather than used solely to mask unfavorable forage characteristics.

Acceptance of *T. diversifolia*-containing diets may contribute to voluntary feed intake when other dietary and animal factors are favorable. Adequate voluntary intake is essential for meeting energy and protein requirements and thereby supporting growth and lactation [57, 135]. However, higher intake does not necessarily result in improved feed conversion because productive efficiency depends on nutrient density, digestibility, maintenance requirements, and the composition of the complete diet.

Consistent acceptance of *T. diversifolia*-containing diets may be associated with lower feed refusals under appropriate feeding conditions, although this relationship should be evaluated through direct measurements of intake and refusals. Studies involving processed or supplemented *T. diversifolia* diets have reported favorable productive responses under selected conditions [14]. Nevertheless, improvements in daily gain, milk yield, reproductive performance, or feed efficiency should be attributed to palatability only when intake-mediated mechanisms are directly demonstrated. Reduced feed waste and lower dependence on purchased feeds remain plausible practical benefits, but their economic importance requires farm level verification [97, 160].

Future development of *T. diversifolia*-based production systems should move beyond evaluation of individual agronomic or nutritional characteristics toward integrated sustainability assessment. Such a framework could combine economic indicators, including feed costs and animal productivity; environmental indicators, including methane emissions, soil carbon dynamics, biodiversity, and erosion; and social dimensions, including labor requirements, smallholder adoption, and local feed security. Future studies should incorporate life cycle assessment (LCA), comprehensive cost–benefit analysis, long-term field validation, and farmer adoption studies to quantify the overall sustainability and economic feasibility of *T. diversifolia*-based systems [80, 92, 94, 114, 141, 144]. Although locally available biomass may have the potential to reduce dependence on purchased feeds, biomass availability alone does not establish an economic advantage because establishment, land, labor, harvesting, transportation, processing, preservation, supplementation, and storage cost must also be considered. Therefore, any economic benefits *T. diversifolia*-based feeding systems should be regarded as provisional until supported by farm-level cost-benefit analyses under specific production conditions.

Research should also address breeding or selection for improved nutritional composition, reduced concentrations of undesirable anti-nutritional compounds, favorable agronomic traits, and greater animal acceptance. Advanced forage preservation approaches and season-specific conservation strategies could further improve year-round availability. These technologies should be evaluated not only for technical effectiveness but also for cost, labor requirements, scalability, storage safety, and suitability for tropical smallholder production systems.

An integrated conceptual framework summarizing the multifunctional role of *T. diversifolia* in tropical ruminant production systems is presented in Figure 2. The framework links forage production and conservation with nutritional improvement, processing technologies, rumen fermentation, methane mitigation, soil nutrient cycling, biodiversity, and socioeconomic outcomes. It also identifies major research priorities, including fermentation optimization, genetic and agronomic improvement, seasonal forage management, LCA, economic evaluation, and supportive implementation strategies. Rather than implying that each pathway provides a proven benefit under all conditions, the framework should be interpreted as a conceptual representation of the interacting nutritional, environmental, and socioeconomic dimensions that require integrated evaluation before widespread adoption.

ANTI-NUTRITIONAL CHALLENGES DESPITE PROCESSING

Residual anti-nutritional factors remain an important limitation in the use of *T. diversifolia* even after fermentation and other processing treatments. Phytic acid, tannins, and oxalates can persist to varying degrees depending on the initial composition of the forage, microbial strain, fermentation duration, temperature, moisture, and processing intensity. Their nutritional significance therefore depends not only on their residual concentrations but also on the composition of the complete diet, animal species, duration of exposure, and mineral and protein supply.

Phytic acid is one of the principal anti-nutritional compounds reported in *T. diversifolia*. Fermentation can substantially reduce its concentration, but complete degradation is not always achieved. Pazla *et al.* [29] reported reductions of approximately 45%–77% under different fermentation conditions involving *L. bulgaricus*. Residual phytate may interact with minerals such as calcium, iron, and zinc and potentially reduce their availability depending on its concentration and the overall dietary context [57]. However, the nutritional importance of residual phytate in ruminants should be interpreted cautiously because ruminal microorganisms can contribute phytase activity and phytate degradation. The extent of any mineral limitation therefore depends on residual phytate concentration, total dietary phytate, ruminal degradation, mineral intake, and physiological requirements.

Tannins may also persist after fermentation. Their nutritional effects are concentration-dependent and should not be regarded as uniformly detrimental. At moderate concentrations, tannins can reduce excessive

ruminal protein degradation and may exert other potentially beneficial effects, whereas high concentrations can reduce palatability, protein digestibility, and feed intake [14]. Residual tannins in processed *T. diversifolia* may therefore remain relevant when concentrations are sufficiently high to interfere with protein utilization. Claims of gastrointestinal irritation or reduced growth should be restricted to situations involving excessive tannin exposure because such effects are not inevitable at all dietary concentrations [91].

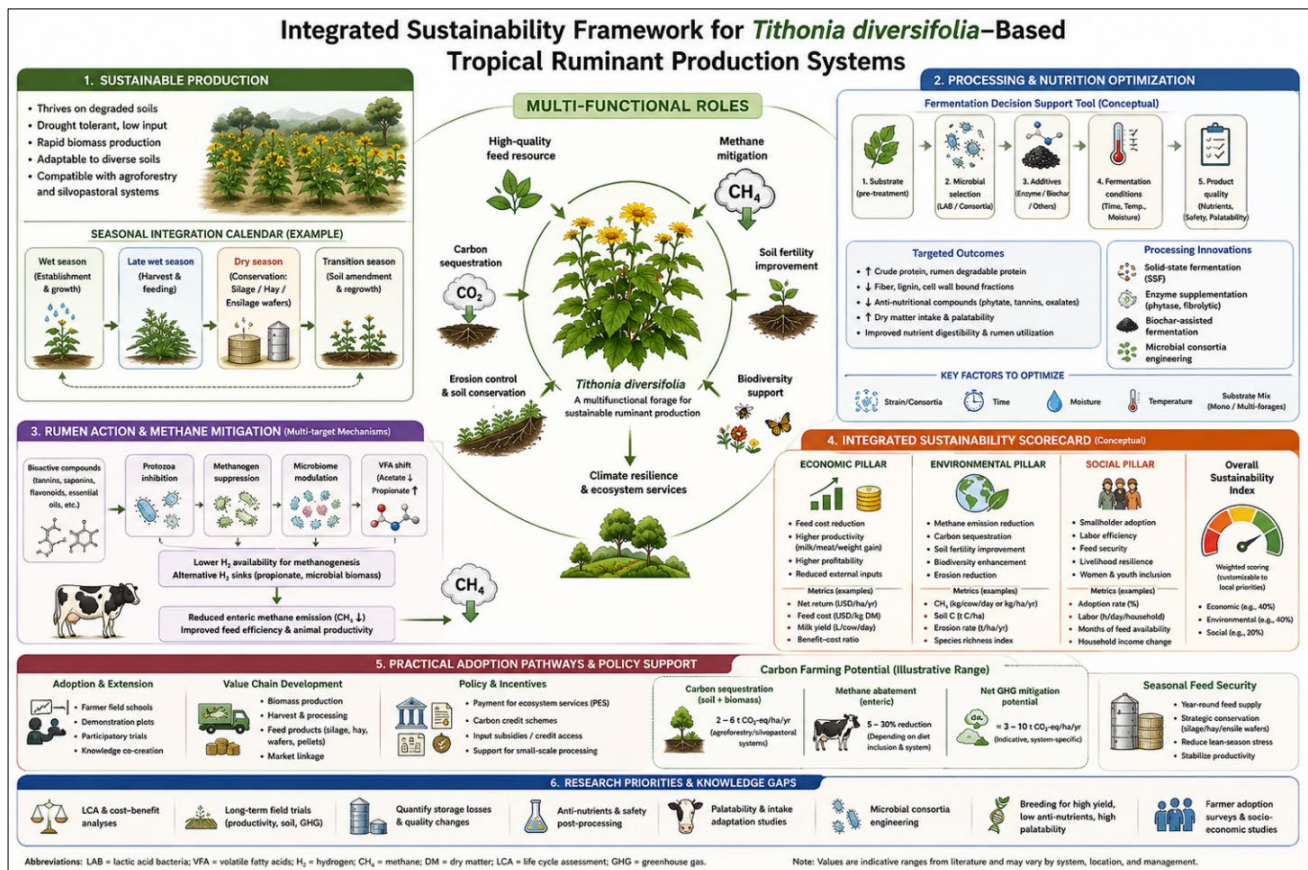


Figure 2: Conceptual framework illustrating the multifunctional role of *Tithonia diversifolia* as a keystone species in redesigned silvopastoral systems.

Oxalates can form complexes with calcium and thereby reduce its availability. Although fermentation and other processing methods may decrease oxalate concentrations, residual amounts can remain [161, 162]. Chronic consumption of high oxalate diets may disturb calcium metabolism in susceptible animals, particularly when dietary calcium supply is inadequate [163]. However, severe outcomes such as urinary calculi, renal damage, or impaired bone mineralization should not be generalized to all *T. diversifolia*-based diets because risk depends on oxalate concentration, dietary mineral balance, adaptation of ruminal microorganisms, duration of exposure, and animal susceptibility.

Persistent anti-nutritional compounds may influence nutrient utilization when their concentrations remain sufficiently high. Phytate can reduce mineral availability, tannins can alter protein digestion, and oxalates can interfere with calcium metabolism [23]. These effects may contribute to nutritional inadequacy if the diet is poorly balanced. Nevertheless, deficiencies in calcium, iron, zinc, or other nutrients should not be attributed solely to residual anti-nutritional factors without direct measurements of intake, absorption, retention, or mineral status.

Residual anti-nutritional factors may also influence feed efficiency and productive performance through reduced digestibility or intake. Where nutrient utilization is impaired, animals may require greater feed intake to achieve equivalent nutrient supply, potentially increasing feeding costs [164]. However, the economic effect depends on forage inclusion level, processing cost, basal diet, animal response, and the price of alternative feed ingredients. Therefore, reduced profitability should be demonstrated through farm level economic analysis rather than inferred directly from chemical composition.

The potential health effects of high residual oxalate or tannin concentrations also require careful interpretation. Prolonged exposure to high oxalate feeds may alter calcium metabolism and contribute to urinary or renal complications in susceptible animals [115]. Excessive tannins may reduce voluntary intake or digestive

efficiency, but moderate concentrations may not produce adverse effects. Risk assessment should therefore be based on dose, exposure duration, dietary balance, and animal-specific tolerance.

Optimization of fermentation conditions remains one of the principal strategies for reducing residual anti-nutritional factors. Adjusting microbial strain, inoculum concentration, temperature, moisture, and fermentation duration can alter phytase activity and the degradation of phytate and other compounds. *L. bulgaricus* has been investigated for its capacity to reduce phytic acid in *T. diversifolia* under controlled fermentation conditions [29]. Nevertheless, no single fermentation protocol can be assumed to eliminate all anti-nutritional compounds, and optimization should focus on achieving nutritionally meaningful reductions while preserving desirable nutrients.

Combining fermentation with additional processing techniques may further reduce anti-nutritional compounds. Soaking can remove some water-soluble components, whereas heat treatment, germination, and other biological or physical approaches may modify selected anti-nutritional factors [165]. However, their effectiveness depends on the specific compound and substrate. Excessive heating can damage heat-sensitive nutrients or reduce protein quality, while soaking may also cause losses of soluble nutrients. Combined processing should therefore be evaluated for both anti-nutritional factor reduction and overall nutrient retention.

Exogenous enzymes provide another potential approach. Phytase can directly hydrolyze phytate and may complement microbial fermentation where residual phytic acid remains high [166]. Its effectiveness depends on enzyme activity, dose, substrate conditions, pH, temperature, and the stage at which it is applied. The use of exogenous phytase should therefore be evaluated in relation to actual improvements in phosphorus availability, mineral retention, animal performance, and cost-effectiveness rather than phytate reduction alone.

Overall, processing can reduce but not necessarily eliminate the anti-nutritional constraints associated with *T. diversifolia*. Future research should quantify residual phytic acid, tannins, oxalates, and other relevant compounds after different processing treatments and relate these concentrations to nutrient digestibility, mineral balance, feed intake, rumen fermentation, animal health, and productive performance. Although concentration-dependent effects are recognized for several of these compounds, practical threshold concentration specifically established for processed *T. diversifolia* remain limited. Establishing such threshold through dose-response and long-term in vivo studies provide a stronger basis for defining safe and nutritionally effective inclusion levels in ruminant diets.

SUMMARY OF KEY FINDINGS

T. diversifolia has considerable potential as an alternative forage for ruminants because of its relatively high protein concentration, favorable mineral composition, adaptability, and capacity for substantial biomass production. Its CP content commonly ranges from approximately 20% to 25% of DM, placing it within the range of several protein-rich tropical forage resources [35, 42]. The forage also provides minerals, including calcium and phosphorus, that can contribute to meeting the nutritional requirements of ruminants [24]. Collectively, these characteristics support its potential as a locally available supplementary feed, particularly in tropical production systems where access to conventional protein sources may be limited or expensive.

Processing can improve the nutritional utilization and preservation of *T. diversifolia*. Fermentation with *L. bulgaricus* has been reported to reduce anti-nutritional compounds, particularly phytic acid, while other processing approaches may also modify tannin concentrations [14]. These changes may improve nutrient accessibility and mineral utilization, although residual anti-nutritional compounds can remain after processing. Fermentation can additionally modify digestibility, preservation characteristics, and sensory properties; however, improvements in palatability and voluntary intake should be verified directly rather than inferred solely from changes in fermentation characteristics.

T. diversifolia also shows potential for modifying ruminal fermentation and reducing enteric methane emissions. Secondary metabolites, including tannins and saponins, may alter microbial fermentation and hydrogen utilization, thereby contributing to lower methanogenesis under certain dietary conditions [93, 167]. The magnitude of methane reduction, however, varies with inclusion level, basal diet, processing method, animal species, and experimental conditions. Consequently, its methane-mitigating potential should be considered alongside animal productivity to determine whether reductions in methane intensity can be achieved without compromising nutrient utilization or productive performance.

Beyond animal nutrition, *T. diversifolia* can contribute to integrated crop–livestock systems through biomass production, nutrient recycling, soil cover, and its use as green manure or mulch. Local cultivation may also reduce dependence on purchased or transported feeds and potentially improve feed security for smallholder producers

[97, 168, 169]. Nevertheless, economic advantages depend on biomass yield, land requirements, harvesting and processing costs, labor, storage losses, animal responses, and the price and availability of alternative feeds. Thus, *T. diversifolia* should be regarded as a multifunctional forage resource whose nutritional, environmental, and economic value depends on the production system in which it is used.

IMPLICATIONS FOR FUTURE RESEARCH AND PRACTICE

A major research priority is to establish the actual bioavailability of nutrients supplied by *T. diversifolia*, particularly its protein and minerals [23, 51]. Phytic acid, tannins, and oxalates can modify mineral and protein utilization, although their effects depend on concentration, processing, dietary composition, and ruminal microbial adaptation. Future studies should therefore quantify nutrient intake, digestibility, mineral balance, nitrogen utilization, and post-ruminal nutrient supply rather than relying primarily on forage chemical composition.

Fermentation optimization remains an important research area. Selection of suitable microbial strains, inoculum concentrations, moisture conditions, temperature, and fermentation duration may improve nutrient preservation and reduce selected anti-nutritional compounds. *L. bulgaricus* has demonstrated potential for reducing phytic acid, but residual concentrations may remain after fermentation. Sari *et al.* [17] and Fauziyah *et al.* [87] provide supporting evidence for the nutritional and biological potential of *T. diversifolia*, although further controlled studies are required to establish processing protocols that consistently improve nutrient availability without causing excessive DM or nutrient losses.

Combining *T. diversifolia* with complementary forage or feed resources, including avocado leaves and sugarcane shoots, represents another area requiring systematic evaluation. Omenda *et al.* [52] and Adekiya [69] provide a basis for considering complementary plant resources and nutrient management approaches, but optimal ingredient proportions remain insufficiently characterized. Future feeding trials should determine appropriate mixing ratios based on nutrient balance, fermentability, palatability, safety, intake, digestibility, and animal performance while also considering the availability and cost of individual ingredients.

Long-term evaluation of *T. diversifolia* within agroforestry and silvopastoral systems is also needed. Its biomass may contribute to OM and nutrients when used as mulch or green manure, potentially influencing soil fertility and nutrient cycling under appropriate management conditions. Botero-Londoño *et al.* [71] and Ewané and Boudjeko [170] provide relevant insights into nutrient cycling and integrated land management; however, these findings should be interpreted within the specific experimental and management conditions of the respective studies and should not be taken as direct evidence of ecosystem-service outcomes across all *T. diversifolia*-based silvopastoral systems. Future studies should quantify changes in soil physical and chemical properties, microbial communities, erosion, nutrient balances, crop and forage productivity, and biodiversity over multiple production cycles. Such research should also consider the potential for uncontrolled spread because *T. diversifolia* can behave invasively in some environments.

The contribution of *T. diversifolia* to climate change mitigation requires particularly rigorous quantitative evaluation. Farni *et al.* [53] highlighted the potential contribution of plant biomass and OM inputs to soil carbon dynamics, but species-specific long-term carbon sequestration rates remain insufficiently established. Similarly, Sari *et al.* [17] and Ewané *et al.* [171] provide evidence relevant to its environmental potential, but further *in vivo* studies should quantify enteric methane responses across dietary inclusion levels and production systems. Research should distinguish absolute methane emissions, methane yield relative to feed intake, and methane intensity relative to animal product output.

Whole-system environmental assessments are needed to determine whether the combined effects of methane mitigation, soil carbon dynamics, nutrient recycling, and reduced dependence on external inputs result in a meaningful net reduction in GHG emissions. LCA should incorporate forage establishment, land use, fertilizer requirements, harvesting, processing, storage, transportation, animal productivity, manure management, and potential soil carbon changes. This approach would provide a more robust assessment of the climate value of *T. diversifolia* than individual measurements of methane or biomass alone.

Economic viability remains fundamental to practical adoption. Comprehensive cost–benefit analyses should compare *T. diversifolia*-based feeding systems with locally relevant conventional alternatives. Endris [54] and Sari *et al.* [172] indicate potential economic advantages associated with locally available resources, but future analyses should account for land opportunity costs, establishment, labor, harvesting, processing, preservation, storage losses, biomass yield, animal performance, transportation, and market conditions. These analyses should be

conducted across different farm sizes and production environments to identify situations in which adoption provides a genuine economic advantage.

The bioactive compounds of *T. diversifolia*, including phenolic compounds, flavonoids, and sesquiterpene lactones, represent another potential area of investigation. Wardhana *et al.* [173] and Elsi *et al.* [16] indicate antioxidant, antimicrobial, or other biological activities associated with *T. diversifolia*. However, evidence from extracts or *in vitro* assays should not be interpreted as proof of therapeutic efficacy in ruminants. Future *in vivo* studies should characterize effective and safe doses, bioavailability, metabolism, potential toxicity, immune and inflammatory biomarkers, interactions with the rumen microbiome, and residues in animal-derived products before therapeutic or ethnoveterinary applications are recommended.

Research should ultimately be translated into practical, region-specific management recommendations. Important considerations include planting density, harvest interval and maturity, biomass yield, conservation during periods of surplus production, safe dietary inclusion levels, processing and fermentation protocols, and strategies for managing seasonal forage shortages. Pazla *et al.* [14] and Yuneldi *et al.* [174] provide a foundation for developing such approaches, but recommendations should be validated under farm conditions across contrasting tropical environments.

Farmer participation should form an integral part of this process. Adoption studies should evaluate labor availability, access to planting material, knowledge requirements, land constraints, willingness to adopt forage conservation technologies, and perceived benefits and risks. Demonstration programs and extension materials can then be developed around technologies that have demonstrated nutritional effectiveness, economic feasibility, environmental benefit, and practical suitability.

Future research should therefore progress from isolated assessments of forage composition toward integrated evaluation of the complete *T. diversifolia* production system. Multidisciplinary studies combining agronomy, feed processing, animal nutrition, rumen microbiology, methane measurements, soil science, LCA, economics, and farmer adoption would provide the evidence required to evaluate the potential role of *T. diversifolia* in climate-smart tropical livestock production.

FINAL THOUGHTS ON SUSTAINABILITY AND RUMINANT NUTRITION

The integration of alternative forage resources such as *T. diversifolia* into livestock production systems represents a promising approach to improving the sustainability, resilience, and resource-use efficiency of tropical ruminant production. Its relatively high nutritional value, adaptability, biomass production, and potential for local cultivation may contribute to feed security and reduce dependence on externally sourced feed ingredients. These characteristics support its potential role in climate-smart livestock systems, particularly in tropical and resource-constrained environments [5, 80, 94].

The value of *T. diversifolia* extends beyond its direct contribution to animal nutrition. Within integrated crop–livestock systems, its biomass can be used both as forage and as an organic amendment or green manure, thereby supporting nutrient recycling and soil fertility. Its secondary metabolites may also modify ruminal fermentation and contribute to reductions in enteric methane emissions under appropriate dietary conditions [24, 70, 94]. In addition, biomass incorporation and integration into agroforestry or silvopastoral systems may contribute to soil OM inputs and carbon cycling. However, these environmental benefits are management- and site-dependent and should not be interpreted as guaranteed reductions in net GHG emissions or increases in long-term carbon sequestration.

The greatest potential of *T. diversifolia* may therefore lie in its strategic integration into diversified, climate-resilient, and low-external-input livestock systems rather than its use as an isolated feed ingredient. Future implementation should combine appropriate forage management, preservation and fermentation technologies, balanced diet formulation, precision feeding, and agroforestry or silvopastoral management. These technological approaches should be accompanied by region-specific extension, farmer participation, economic evaluation, and supportive implementation strategies [6, 80, 155]. Such an integrated approach could facilitate responsible adoption of *T. diversifolia* while providing a framework for evaluating other underutilized tropical forage resources.

RECOMMENDATIONS FOR FUTURE RESEARCH AND PRACTICAL APPLICATION

Future research should determine the long-term effects of *T. diversifolia* inclusion on nutrient utilization, animal health, productive performance, and product quality. Particular attention should be given to the

bioavailability of protein and minerals and to the residual concentrations and biological significance of anti-nutritional compounds after processing. Studies should evaluate fermentation conditions, microbial strains, inoculum concentrations, enzyme supplementation, and combined processing strategies to identify approaches that improve nutrient retention while effectively reducing undesirable compounds. Ovani *et al.* [78] provide relevant evidence supporting continued evaluation of processing and management strategies.

Long-term *in vivo* feeding trials are required to establish safe and effective inclusion levels across different ruminant species, physiological stages, and basal diets. These studies should simultaneously measure voluntary intake, nutrient digestibility, rumen fermentation, nitrogen utilization, mineral balance, animal health indicators, productive performance, and product quality. Such integrated measurements would provide a stronger basis for practical feeding recommendations than assessments based primarily on forage chemical composition.

Further research should also establish the economic feasibility of *T. diversifolia*-based feeding systems relative to locally relevant conventional feeds. Hassan *et al.* [90] support the need for context-specific evaluation. Economic analyses should incorporate establishment and land costs, biomass yield, harvesting and transportation, labor, processing and fermentation, storage losses, supplementation requirements, animal performance, and local feed and livestock-product prices. Cost–benefit analysis conducted across contrasting production environments would clarify the conditions under which *T. diversifolia*-based feeding may be economically feasible.

The climate mitigation potential of *T. diversifolia* also requires more rigorous quantitative investigation. Future studies should directly measure enteric methane emissions and determine whether reductions persist across inclusion levels, processing methods, basal diets, and production systems [75]. Research should distinguish between absolute methane emissions, methane yield relative to feed intake, and methane intensity relative to animal output. Long-term field studies are also required to quantify changes in soil carbon stocks associated specifically with *T. diversifolia* biomass management and its integration into agroforestry or silvopastoral systems. These measurements should ultimately be incorporated into whole-system assessments. LCA can be used to determine whether changes in enteric methane, feed production, fertilizer use, land management, soil carbon, transportation, processing, and animal productivity translate into a net reduction in GHG emissions. Such analyses are necessary before *T. diversifolia* can be recommended specifically as a climate mitigation intervention.

Practical implementation requires region-specific recommendations for establishment, planting density, harvest maturity and frequency, seasonal biomass conservation, processing, ensiling, storage, and dietary inclusion. Where evidence remains insufficient, these management parameters should be treated as research priorities rather than universal farmer recommendations. Management protocols should account for differences in rainfall, soil fertility, forage availability, animal requirements, and farm resources. Appropriate management should also address the potential invasiveness of *T. diversifolia* and prevent unintended spread into surrounding ecosystems.

Farmer-centered extension and training are equally important for translating research findings into practice. Programs should provide evidence-based guidance on planting, harvesting, preservation, diet formulation, and safe utilization of *T. diversifolia* [14, 174, 175]. Participatory on-farm studies can further identify practical constraints related to labor, land availability, access to planting material, processing infrastructure, and farmer acceptance. Integrating these socioeconomic considerations with nutritional and environmental evidence will provide a more realistic basis for adoption.

Overall, future research should progress from short-term evaluations of individual nutritional or agronomic characteristics toward multidisciplinary, long-term assessment of complete *T. diversifolia*-based production systems. Combining animal nutrition, rumen microbiology, forage agronomy, soil science, environmental assessment, economics, and farmer adoption will be essential for determining whether the nutritional and environmental potential identified in this review can be translated into practical, scalable, and sustainable tropical ruminant production.

CONCLUSION AND FUTURE DIRECTIONS

T. diversifolia has considerable potential as a multifunctional forage resource for tropical ruminant production because of its relatively high nutritional value, substantial biomass production, adaptability, and potential integration into crop–livestock and agroforestry systems. Evidence reviewed in this article indicates that its CP content, mineral composition, and bioactive compounds can contribute to ruminant nutrition, while fermentation and other processing strategies can improve its utilization. However, its practical value is influenced by plant maturity, growing conditions, soil fertility, processing method, dietary inclusion level, and the

characteristics of the production system [14, 22, 53, 76].

A major constraint to wider utilization is the presence of anti-nutritional compounds, particularly phytic acid, tannins, and oxalates. Although fermentation and other processing methods can reduce their concentrations, complete elimination is not always achieved. Pazla *et al.* [29] reported substantial reductions in phytic acid following fermentation with *L. bulgaricus*, although residual concentrations remained. The nutritional significance of these residual compounds should be evaluated in relation to nutrient digestibility, mineral balance, ruminal degradation, and animal requirements rather than chemical concentration alone [57]. Future research should therefore optimize microbial strains, inoculum concentrations, fermentation duration, moisture, temperature, and complementary processing technologies to maximize nutrient retention while minimizing undesirable compounds [106, 135].

The integration of *T. diversifolia* into agroforestry and silvopastoral systems represents another important research opportunity. Its biomass can contribute to soil nutrient recycling when used as green manure or mulch, while its adaptability may facilitate incorporation into diversified tropical production systems. Ma *et al.* [176] reported beneficial effects associated with green manure applications, whereas Omenda *et al.* [52] demonstrated its relevance to phosphorus mobilization and nutrient cycling. However, long-term studies are required to determine how *T. diversifolia* interacts with associated plant species and influences soil properties, microbial communities, biodiversity, water use, erosion, and overall system productivity. Its potential invasiveness should also be incorporated into ecological risk assessment and management strategies.

Economic feasibility will ultimately determine whether *T. diversifolia* can be adopted widely by smallholder livestock producers. Although local forage production and biomass recycling may reduce dependence on purchased feeds or fertilizer inputs, these potential savings must be considered against establishment, land, harvesting, labor, processing, conservation, transportation, and storage costs. Fauziyah *et al.* [87] highlighted biological properties of *T. diversifolia* that warrant further investigation, whereas Akinrinola *et al.* [168] demonstrated the potential value of its biomass in soil fertility management. Comprehensive cost–benefit and whole-farm analyses are needed to determine whether these biological and agronomic advantages translate into measurable financial benefits under different production conditions.

The environmental implications of *T. diversifolia* also require rigorous quantitative assessment. Dietary inclusion may alter ruminal fermentation and reduce enteric methane production under certain conditions [30]. However, methane formation is mediated primarily by methanogenic archaea, and protozoa contribute indirectly through their ecological interactions and hydrogen production; therefore, methane mitigation should not be attributed simply to inhibition of “methane-producing protozoa.” Long-term *in vivo* studies should quantify absolute methane emissions, methane yield relative to feed intake, and methane intensity relative to animal output across different inclusion levels, basal diets, processing methods, and ruminant species.

Similarly, incorporation of *T. diversifolia* biomass into soil can increase OM inputs, but this should not automatically be equated with long-term carbon sequestration. Field studies are required to quantify changes in soil carbon stocks over time and distinguish short-term biomass turnover from persistent carbon storage. LCA should subsequently integrate enteric methane, soil carbon dynamics, fertilizer use, land requirements, forage production, processing, transportation, manure management, and animal productivity to determine the net GHG implications of *T. diversifolia*-based production systems.

Bioactive constituents of *T. diversifolia* also warrant further investigation. Wardhana *et al.* [173] and Elsi *et al.* [16] reported biological activities associated with the plant and its extracts, indicating potential antioxidant, anti-inflammatory, antimicrobial, or immunomodulatory properties. However, evidence derived from extracts, laboratory assays, or *in vitro* experiments should not be interpreted as proof of therapeutic efficacy in livestock. Future studies should characterize active compounds, mechanisms of action, bioavailability, effective doses, toxicity, interactions with the rumen microbiome, and potential residues in animal-derived products. Controlled *in vivo* studies are required before *T. diversifolia* extracts can be considered alternatives or complements to conventional veterinary therapeutics.

The literature synthesized in this review, including *in vitro* and *in vivo* investigations, demonstrates that *T. diversifolia* can provide a nutrient-rich forage resource for ruminants. Its CP concentration commonly ranges from approximately 20% to 25% of DM, and it supplies minerals such as calcium and phosphorus. Its nutritional value varies with plant maturity, growing conditions, soil fertility, environmental conditions, and processing methods [14, 22, 53, 76]. Much of the evidence reviewed originates from tropical production systems, particularly Indonesia [14, 23, 51, 58], while studies from other tropical regions also support further evaluation of the species

as a ruminant forage [24, 56, 67, 76]. Its biomass productivity and adaptability strengthen its potential for smallholder production systems [22, 24], although performance remains dependent on local agronomic and management conditions.

Fermentation with LAB can improve selected characteristics of *T. diversifolia*, particularly by reducing some anti-nutritional compounds and modifying nutrient availability. Nevertheless, fermentation does not eliminate all nutritional constraints, and improvements in mineral bioavailability, digestibility, palatability, or animal performance should be verified directly under relevant feeding conditions. Seasonal biomass availability, forage conservation, animal acceptance, residual anti-nutritional compounds, labor requirements, and appropriate dietary inclusion levels remain important practical constraints.

Future research should prioritize six interconnected areas: (i) improving nutrient bioavailability through optimized fermentation, microbial consortia, enzyme supplementation, and complementary processing approaches; (ii) validating long-term *in vivo* effects on intake, digestibility, animal productivity, health, reproduction, and product quality; (iii) elucidating rumen microbiome responses and methane mitigation mechanisms using appropriate molecular and multi-omics approaches; (iv) conducting LCA, long-term soil-carbon measurements, and comprehensive economic analyses to quantify environmental and financial outcomes; (v) developing region-specific decision-support tools for cultivation, harvesting, conservation, processing, and dietary inclusion; and (vi) strengthening farmer-centered extension, participatory validation, and appropriate policy support to facilitate evidence-based adoption.

Overall, *T. diversifolia* should be considered a promising multifunctional forage rather than a universally superior replacement for conventional feeds. Its greatest value is likely to emerge when nutritional use, forage conservation, soil nutrient recycling, environmental management, and socioeconomic feasibility are integrated within the same production system. Addressing the remaining nutritional, agronomic, environmental, and economic uncertainties will be essential for determining the extent to which *T. diversifolia* can contribute to climate-resilient, low-external-input ruminant production in tropical regions and provide a model for the responsible utilization of other underused tropical forage resources [5, 6, 80, 94].

DATA AVAILABILITY

All data supporting this review are available from the published literature cited in the manuscript. No new data were generated or analyzed for this study.

GENERATIVE AI DECLARATION

The authors declare that generative artificial intelligence (AI) tools were used solely to improve language, grammar, and readability during manuscript preparation. All scientific content, data analysis, interpretation of results, and conclusions were developed and verified by the authors. The authors take full responsibility for the accuracy, integrity, and originality of the work presented, and no AI tool was listed as an author.

AUTHORS' CONTRIBUTIONS

RP, AA, YF, and LM: Drafted the manuscript, conceptualization, review & editing, and validation. TH, SA, HFPP, and NN: Drafted, revised, validation and edited the manuscript. PL, RWA, and AY: Drafted, critically revised the manuscript, project administration, software, and validation. IS, RH, JH, GHJ, and WD: Drafted and finalized the manuscript. All authors have read and approved the final version of the manuscript.

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COMPETING INTERESTS

The authors declare that they have no competing interests.

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