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Overcoming the Challenges of Silage Production: Insight into the Importance of Silage Additives

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Abstract. The lack of high-quality feed remains a critical global challenge that demands that demands long¬term, sustainable solutions. Ensiling has emerged as a key strategy for preserving forage; yet significant challenges persist, particularly regarding nutrient losses and aerobic spoilage during storage. Poor silage quality not only reduces the net nutritional value of the feed but also adversely affects herd health and productivity. This review provides a comprehensive overview of recent advancements in silage technology, focusing on the pivotal role of additives in enhancing fermentation dynamics, preserving essential nutrients, and maintaining post-opening aerobic stability. The biochemical profile of the feedstock significantly dictates the specific requirement for additives, ranging from water-soluble carbohydrate sources and bacterial inoculants to chemical enzymes and organic acids. Unlike previous literature that predominantly focuses on temperate forages, this study highlights the integration of underutilized tropical biomass resources, such as cassava leaves and oil palm fronds. Furthermore, it explores novel biotechnological interventions, including microencapsulation and multi-omics technologies, which offer innovative pathways to optimize additive efficiency. By bridging conventional conservation practices with advanced molecular tools, this study highlights the potential of silage additives to provide a sustainable, resilient, and region-specific feed supply for the modern livestock sector.

Keywords: aerobic stability, ensilage, fermentation quality, silage additives, tropical biomass

Abstrak. Ketersediaan pakan berkualitas tinggi tetap menjadi tantangan global yang menuntut solusi berkelanjutan. Silase telah muncul sebagai strategi kunci untuk mengawetkan pakan ternak, tetapi tantangan signifikan masih ada, terutama hilangnya nutrisi dan pembusukan selama penyimpanan. Kualitas silase yang buruk tidak hanya mengurangi nilai nutrisi, tetapi juga mengganggu kesehatan dan produktivitas ternak. Tinjauan ini memberikan analisis komprehensif tentang kemajuan terkini dalam teknologi silase, dengan fokus pada peran penting aditif dalam meningkatkan dinamika fermentasi, pengawetan nutrisi, dan stabilitas aerobik. Karakteristik biokimia bahan baku sangat memengaruhi jenis aditif yang dibutuhkan, mulai dari sumber gula karbohidrat larut air dan inokulan bakteri hingga enzim fungsional dan asam organik. Berbeda dengan tinjauan sebelumnya yang terutama menekankan hijauan beriklim sedang, artikel ini menyoroti integrasi sumber daya biomassa tropis yang belum dimanfaatkan secara optimal seperti daun singkong dan pelepah kelapa sawit. Lebih lanjut, tinjauan ini mengeksplorasi pendekatan bioteknologi yang sedang berkembang, termasuk mikroenkapsulasi dan perangkat multi-omik yang menawarkan peluang baru untuk mengoptimalkan aplikasi aditif. Dengan menjembatani praktik konvensional dengan teknologi canggih, tinjauan ini menggarisbawahi potensi aditif silase untuk memastikan pasokan pakan yang berkelanjutan, tangguh, dan spesifik wilayah bagi sektor peternakan.

Kata kunci: aditif silase, biomassa tropis, ensilase, kualitas fermentasi, stabilitas aerobik

Introduction

Silage is the outcome of fermentation and anaerobic acidification, which is used to preserve green fodder and turn organic feed into a more durable and nutritious form (Grant and Adesogan, 2018). The ruminant livestock sector is predicted to grow, which will lead to more global demand for silage (Karnatam et al., 2023). Silage manufacturing has an important role in ensuring feed availability and nutritional security for ruminants, particularly in tropical regions where severe seasonal conditions often limit forage quality. However, tropical forages inherently present poor fermentation profiles and high risks of nutritional degradation due to their high moisture content, advanced lignification, and low concentrations of fermentable sugars (Queiroz et al., 2018; Zi et al., 2022; Zielińska et al., 2017).

These biochemical constraints often result in extensive nutrient leaching, secondary clostridial fermentation, and rapid aerobic deterioration upon silo opening, challenging the year-round supply of stable feed resources. Consequently, new approaches are necessary to optimize the utilization of locally sourced biomass for the production of silage with enhanced fermentation quality, total-tract digestibility, and livestock palatability (Irawan et al., 2021; Wang et al., 2021). The utilization of additives has become an important approach to mitigate these these preservation bottlenecks by facilitating lactic acid fermentation, suppressing opportunistic spoilage microorganisms, and fortifying post-ensiling aerobic stability (Oladosu et al., 2016). Recent advances emphasize the shift toward bio-based or microbial-derived additives. These eco-friendly formulations optimize fermentation efficiency and also support sustainable and eco-friendly livestock production systems consistent with global green-agriculture goals.

Although research on silage additives, including the mechanisms linking additive type, plant characteristics, and fermentation dynamics, has been extensively documented, it remains insufficiently integrated. Most existing studies evaluate single-additive categories, such as standalone LAB inoculants or isolated enzymatic treatments, without providing a holistic analysis of their synergistic or antagonistic dynamics across diverse tropical substrates and varying storage temperatures. Furthermore, how complex additive combinations influence microbial succession, multi-metabolite profiles and nutrient retention, and post-silage aerobic stability in tropical environments remains poorly explored. Moreover, from a practical perspective, long-term sustainability assessments and economic evaluations of additive usage are rarely recorded, hindering the implementation of evidence-based additive practices by farmers and the industry. This review aims to highlight the functional roles of silage additives in overcoming the distinctive production challenges of tropical ensiling. Specifically, it emphasizes recent innovations in additive applications technologies that enhance nutritional quality, support herd performance, and sustainable livestock production systems.

Materials and Methods

Literature Search Strategy

This review was conducted through a comprehensive literature survey to evaluate the role of silage additives in improving fermentation quality, nutrient preservation, and aerobic stability across diverse forage resources, with particular emphasis on tropical biomass. Relevant peer-reviewed publications were retrieved from major electronic databases and indexing platforms, including Scopus, Web of Science, PubMed, supplemented by targeted searches within ScienceDirect and Google Scholar.

The literature search encompassed studies published between 2014 and 2026. Search strings were constructed using Boolean operators (AND/OR) to combine the following keywords: (silage additives OR silage inoculants OR organic acids OR enzymes OR water-soluble carbohydrates) AND (ensiling OR silage fermentation OR aerobic stability OR microbiome OR metabolomics) AND (tropical biomass OR cassava leaves OR oil palm fronds OR elephant grass OR crop residues).

Study Selection and Eligibility Criteria

Studies were included in this review if they met the following strict eligibility criteria: (1) original research articles or comprehensive review papers published in peer-reviewed journals; (2) focused directly on silage production, fermentation dynamics, additive applications, microbial inoculants, enzymatic treatments, nutrient supplementation, or aerobic stability; (3) reported quantifiable outcomes related to silage quality, including pH, organic acid profiles, dry matter preservation, nutrient composition, microbial community dynamics, digestibility, or aerobic deterioration; and (4) provided transparent methodological information and experimental setups for critical evaluation.

Publications were excluded if they were conference abstracts without full-text availability, book reviews, duplicate publications, articles published in languages other than English, or studies unrelated to silage fermentation and preservation parameters.

Data Extraction and Synthesis

Information extracted from the selected eligible studies included biomass type, additive category, specific inoculant strain, application rate, fermentation duration, physicochemical characteristics, microbial responses, and key indicators of silage quality. The collected data were organized into the following thematic categories: (1) ensiling dynamics and quality degradation, (2) crop resources for silage production, (3) microbial inoculants, (4) chemical and enzymatic additives, (5) nutrient supplements and carbohydrate sources, and (6) emerging biotechnological approaches for silage improvement.

A qualitative synthesis approach was employed to compare findings across different experimental setups and identify common trends, technical challenges, and research gaps. Special attention was dedicated to studies utilizing tropical biomass resources due to their critical role in developing sustainable livestock production systems in tropical and subtropical regions.

Quality Assessment

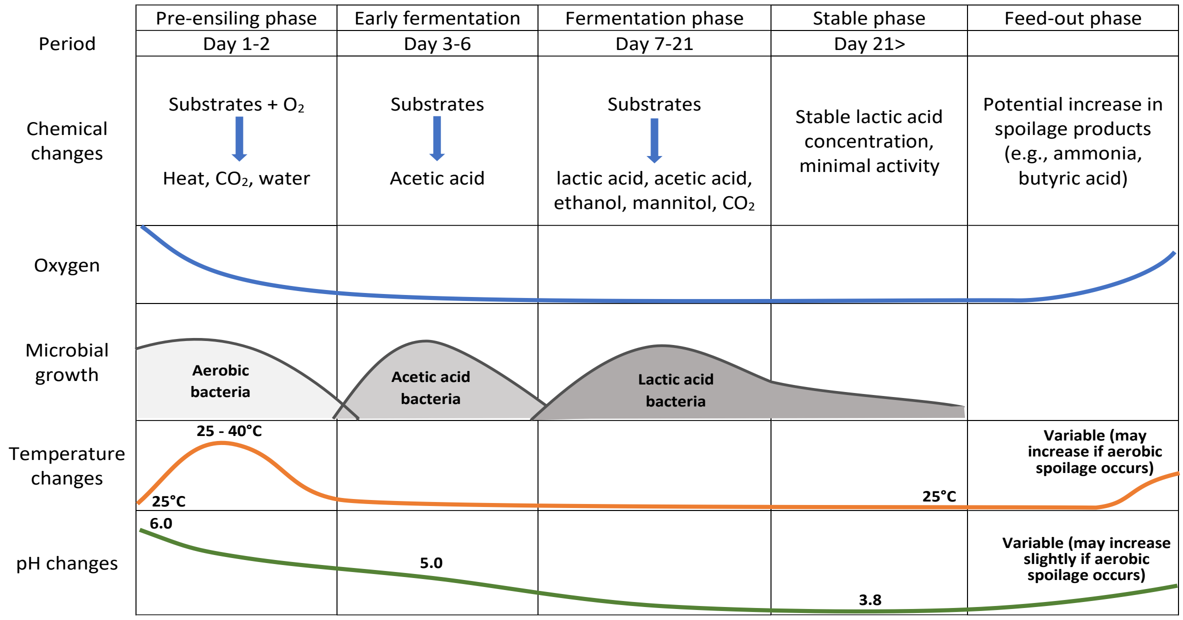
The technical reliability of the selected literature was evaluated based on experimental design validity, clarity of methodology, detailed sample description, robustness of analytical approaches, and direct relevance to silage fermentation. Priority was given to studies providing quantitative, replicated evidence on the effects of silage additives, ensuring that the synthesized trends are based on statistically sound scientific data.

Results and Discussion

Ensilage Dynamic and Quality Degradation

Ensilage is a well-established preservation method, although the biological processes are quite complex and depend on various factors, including the variety of epiphytic microbial diversity, harvesting conditions, forage chemical composition, ambient temperature, and plant enzymatic activity (Witariadi and Putri, 2018). Silage fermentation generally proceeds through four phases: pre-silage, initial and main fermentation, the stable phase, and the terminal feeding phase (Ávila and Carvalho, 2020). Figure 1 shows the four sequential phases: (1) pre-silage aerobic phase, (2) initial and main anaerobic fermentation, (3) stable storage phase, and (4) terminal feed-out phase upon aerobic exposure.

The pre-ensiling phase initiates immediately upon biomass harvest, chopping, and wilting. The process of wilting effectively reduces the moisture content of the raw biomass to an optimal 60–70% (Du et al., 2023). During this phase, aerobic respiration by both epiphytic microorganisms and the biomass itself remains active, generating metabolic energy that is released into the mass as heat (Muck et al., 2018). Once the biomass is thoroughly compacted and within the silo, residual oxygen is rapidly depleted, thereby lowering the pH and inhibiting obligate aerobic microbial activity (Weiß et al., 2022).



Source: Jones (2023)

Figure 1. The four sequential phases of the ensiling process and quality dynamics

The fermentation phase occurs when anaerobic conditions take over, subdivided into initial and main fermentation. Under these anaerobic dynamics, facultative anaerobic bacteria such as *Bacillus* and *Enterobacteriaceae*, followed by lactic acid bacteria (LAB), play a role in converting soluble carbohydrates into lactic acid, acetic acid, ethanol, and CO_2 (Wang et al., 2021). Usually, in the second week, LAB activity peaks, lowering the pH to 3.8–5.0, which is crucial for silage preservation (Khota et al., 2016).

The stable phase is characterized by minimal microbial activity and negligible chemical alterations. The established dominance of lactic acid bacteria (LAB) maintains a low pH environment, effectively suppressing undesirable microbes such as Enterobacteriaceae and Clostridia (Sun et al., 2023; Wilkinson and Rinne, 2018). However, secondary instability can still occur if microbial dynamics shift, depending on the type of biomass, geography, harvest time, and the specific inoculant applied (Guan et al., 2020).

The feed-out phase begins when the silo is opened for animal feeding, which provides an opportunity for anaerobic silage packaging to be untied, exposing it to oxygen. This exposure allows opportunistic airborne aerobic microorganisms, such as acid-tolerant molds and yeasts, to rapidly proliferate. These organisms metabolize residual organic acids, particularly lactic acid, which subsequently elevates the silo pH and allows the growth of spoilage organisms (Driehuis et al., 2018). This phase substantially reduces the nutritional value of the silage and increases the risk of mycotoxin contamination.

Aerobic exposure triggers severe nutrient depletion through leaching during fermentation, especially when the humidity is high and the material is not well-compacted. This makes aerobic respiration last longer, which causes the loss of water-soluble nutrients (Yang et al., 2022). Insufficient compaction allows oxygen to penetrate deeper into the silage core and aerobic respiration to continue, which causes the loss of fermentable carbohydrates and other important nutrients, especially protein and amino acids. Additionally, under high-moisture conditions, uncompacted material exacerbates effluent leaching, leading to further loss of highly digestible nutrients (Weiß et al., 2022; Wilkinson and Rinne, 2018). The cumulative result of these degradations is a low-quality, nutrient-depleted feed that exhibits severely compromised palatability and reduced in vivo digestibility for livestock (de Carvalho et al., 2018).

Crops for Silage

The inherent diversity of silage crops presents a unique opportunity and a challenge in achieving uniform and predictable fermentation quality consistently. Table 1 indicates that grasses typically serve as an ideal substrate for lactic acid fermentation due to their substantial water-soluble carbohydrate (WCS) content and a moderate buffering capacity. Conversely, while legumes and crop residues offer more nutritious, options, they possess biochemical constraints such as high buffering capacities and lower initial sugar levels that delay acidification and elevate the risk of clostridial spoilage. Furthermore, the emerging utilization of energy and woody crops expands the biomass base for silage production, yet simultaneously introduces structural barriers related to advanced lignification and low fermentable sugar content.

Classification of silage crops extends beyond the mere botanical aspect; it delineates the precise biochemical environment in which subsequent silage additives must function. Consequently, understanding these biochemical boundaries is essential for tailoring microbial inoculants, enzymes, and nutrient supplements to make sure that fermentation, nutrient retention, and aerobic stability work well in different agroecosystems. The different fermentation characteristics of each crop type require demand-targeted, substrate-specific strategies to successfully optimize the ensiling process.

In tropical regions like Indonesia, different local biomass sources have been found as potential raw materials to produce silage based on the availability and adaptability to local agroecosystem conditions.

Table 1. Biochemical and fermentation characteristics of different silage crop categories (grasses, legumes, crop residues, and energy crops)

Plant Group	Representative Species	General Fermentation Characteristics	References
Grasses	*Zea mays* (maize), *Sorghum bicolor* (sorghum), *Triticum aestivum* (wheat), *Panicum miliaceum* (millet), *Panicum maximum* (Tanzania grass), and other tropical grasses	High water-soluble carbohydrate (WSC) content, rapid and stable fermentation, moderate moisture, and good lactic acid production	Bernardes and Do Rêgo, (2014); Cieślik et al. (2016); Flores et al. (2021); Oliveira et al. (2018)
Legumes	Perennial legumes such as *Medicago sativa* (alfalfa) and related species	High crude protein and buffering capacity; low WSC; require molasses or inoculant supplementation	Aloba et al. (2022); Busato et al. (2019)
Crop Residues and Straw	*Oryza sativa* straw (rice straw), maize stover	High fiber and lignin; low sugar availability; require enzymatic or chemical pretreatment	Cieślik et al. (2016); Mafefa et al. (2023)
Energy and Non-conventional Biomass Crops	*Arundo donax* (giant reed), *Helianthus tuberosus* (Jerusalem artichoke)	High biomass yield; slow fermentation; require additives to improve pH stability and fermentation efficiency	Giertl et al. (2022)
Woody Plants	*Salix alba* (willow), *Populus canadensis* (poplar)	High lignocellulose content; low fermentability; often mixed with WSC-rich forages to balance nutrients	Du et al. (2023)
Tropical Mixed or Multi-species Silage	Mixtures of tropical grasses, legumes, and crop residues	Balanced sugar–protein profile; suitable for tropical systems; improved fermentation with inoculants	Bernardes and Do Rêgo (2014)

There are many plants that can be used for silage, including cassava leaves, elephant grass (*Pennisetum purpureum*), sugar cane bagasse, and oil palm fronds (Anjalani et al., 2017; Wijayanti et al., 2022). Furthermore, aquatic plants such as water hyacinth (*Eichhornia crassipes*), various tropical grass species like *Setaria sphacelata, Pennisetum purpureophoides*, and *Panicum maximum*, and protein-rich legume plants like lamtoro (*Leucaena leucocephala*) and calliandra (*Calliandra calothyrsus*) offer diversified options for feed preservation (Nguyen et al., 2016; Santoso et al., 2015; Sumarsih et al., 2018). Concurrently, agro-industrial by-products, particularly sugarcane bagasse and oil palm fronds, hold immense promise as sustainable, low-cost raw materials for industrial-scale silage processing. This rich diversity and ecological adaptability underscore the necessity of establishing region-specific silage strategies that effectively integrate proper crop selection, targeted additive applications, and fermentation protocols tailored to local agroecological realities.

The selection matrix of biomass for ensiling strategy depends on several primary factors, such as high water-soluble carbohydrates (WSC), a low inherent buffering capacity, and an optimal moisture level ranging between 60-70% (Du et al., 2023; Zi et al., 2022). Additionally, maturity at harvest also greatly influences the silage quality. Harvesting biomass at an early vegetative stage yields a superior WSC concentration and lower structural fiber fractions, which accelerates the onset of anaerobic fermentation and maximizes nutrient retention (Suryanah et al., 2018; Wilkinson and Rinne, 2018). These dynamics highlight the critical need to thoroughly evaluate distinct botanical characteristics when selecting raw components for feed manufacturing (McCary et al., 2020; Pecka-Kiełb et al., 2021). Given the wide biochemical variations across these tropical substrates, the strategic application of tailored silage additives is frequently vital to ensure predictable fermentation efficiency and robust nutrient preservation.

Silage Additives

The primary challenge in ensiling is the rapid degradation of silage quality caused by aerobic exposure, which directly leads to severe nutrient and dry matter loss (Liu et al., 2023; Queiroz et al., 2018). Additionally, high buffering capacity inherent to biomass types presents another critical bottleneck by delaying the necessary pH drop during the early phases of fermentation (Schneider et al., 2021).

To counteract these limitations, additive strategies are widely deployed to enhance fermentation efficiency, preserve nutritional value, and mitigate aerobic spoilage. Researchers continue to explore various types of additives that are suitable and effective in improving silage quality. To solve the natural variability between crops, comprising microbial inoculants, chemical enzymes, organic acids, water-soluble carbohydrate (WSC) sources, and target nutrient supplements are strategically utilized (Figure 2).

Microbial Inoculants

Lactic acid Bacteria (LAB)

Lactic acid bacteria (LAB), comprising both homofermentative and heterofermentative strains, represent the cornerstone of silage inoculants due to their capacity to convert water-soluble carbohydrates (WSC) into lactic acid, thereby driving a rapid pH decline and suppressing epiphytic spoilage organisms (Sun et al., 2023). In addition, they also reduce protein degradation and ammonia-N accumulation (Oladosu et al., 2016).

Homofermentative LAB, such as *Lactobacillus acidophilus, Lacticaseibacillus casei, and Lactiplantibacillus plantarum,* utilize the Embden-Meyerhof-Parnas pathway to efficiently maximize lactic acid yield and rapidly drop the silo pH (Ertekin and Kizilşimşek, 2019; Hu et al., 2020; Zhao et al., 2022).

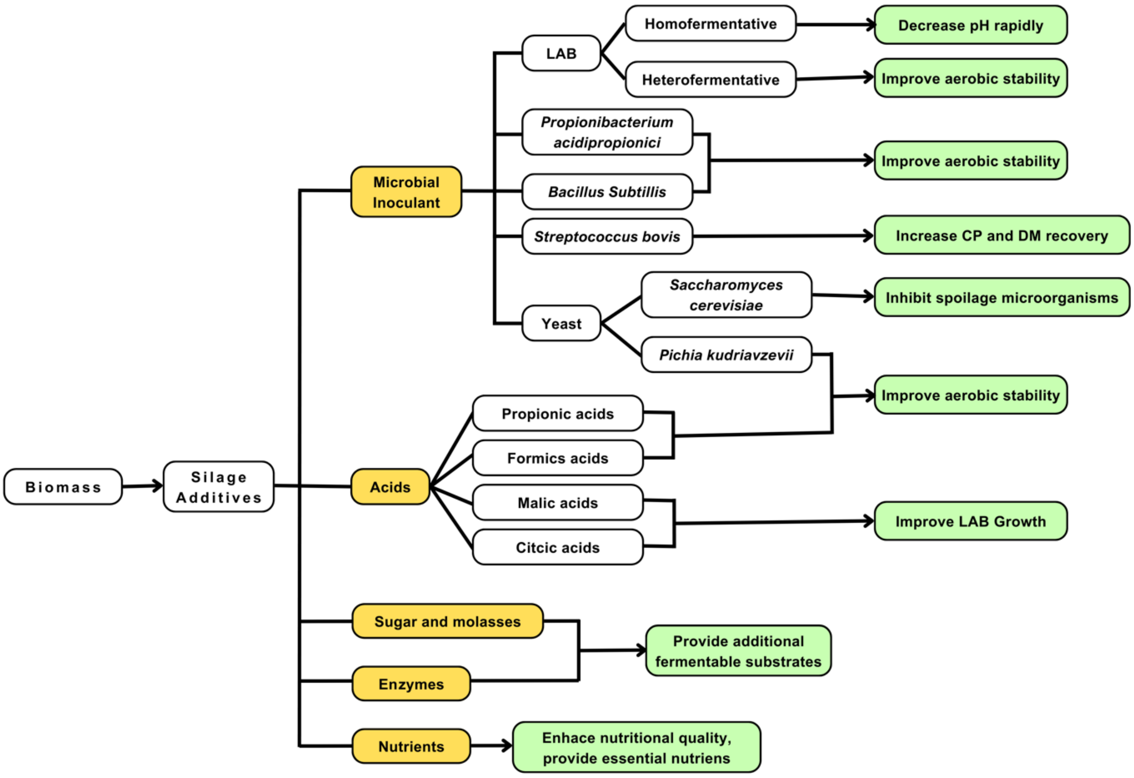


Figure 3. Role of additives on silage production

Beyond organic acid production, specific strains, including *L. acidophilus, L. casei, Companilactobacillus crustorum, Pediococcus acidilactici*, and *Lentilactobacillus buchneri,* secrete active antimicrobial metabolites, such as 3-phenyllactic acid and azelaic acid, which further inhibit fungal growth (Ponzio et al., 2024).

Conversely, heterofermentative LAB, including *Lentilactobacillus buchneri, L. hilgardii,* and *L. brevis,* catabolize WSC via the pentose phosphate pathway to generate acetic acid, ethanol, and CO_2, which enhances post-opening aerobic stability; this pathway inherently incurs higher dry matter (DM) losses (Ferrero et al., 2021; Stephen and Saleh, 2023). To optimize preservation, combined inoculants (e.g., *L. buchneri* + *Enterococcus faecium*) provide a synergistic effect by balancing rapid acidification with long-term stability, especially useful for tropical silage that is susceptible to aerobic rot (Jatkauskas et al., 2025).

The use of LAB in silage typically occurs at a concentration of 1 × 10^6 CFU/g and can be applied in liquid inoculum form or as freeze-dried powder (Santoso et al., 2015). Changes in silage quality depend heavily on the type of inoculant and biomass used. The composition of LAB additives as inoculants for various types of biomass and their effect on silage quality are presented, confirming the high suitability of these crops for additive-assisted conservation in Table 2.

Other Microbial Inoculants

Other microbial additives include Streptococcus bovis, which produces bacteriocins and enhances CP and DM (de Moura Zanine et al., 2018). Other bacteria, such as *Bacillus subtilis*, can inhibit spoilage microorganisms, increase aerobic stability (Bai et al., 2020), and improve the nutritional quality of silage (Bonaldi et al., 2021).

Table 2. Applications of microbial inoculants across various biomass substrates and their subsequent effects on silage fermentation quality and nutrient preservation

Biomass	Inoculant	Treatment	Ensiling duration (days)	DM (% FM)	CP (% DM)	WSC (% DM)	pH	LA (%)	AA (%)	Reff.
Mulberry leaf	*L. casei*	Control	60	29.44	20.94	1.69	4.6	4.16	1.07	1
		Inoculated		31.04	21.08	1.1	4.03	5.95	0.84	
Alfalfa	*L. casei*	Control	56	26.81	-	1.48	5.24	4.48	1.05	2
		Inoculated		28.13	-	1.87	4.6	6.15	0.58	
Sunflower plant	*L. buchneri*	Control	60	29.2	13.5	-	3.31	-	-	3
		Inoculated		25.9	13.1	-	3.19	-	-	
Whole-plant Corn	*L. buchneri*	Control	90	22.8	0.86	0.21	3.95	6.06	0.96	4
		Inoculated		24.2	0.86	0.16	3.86	6.16	4.72	
Rice straw + Amaranth	*L. Plantarum*	Control	30	34.2	5.53	0.8	4.19	2.86	1.32	5
		Inoculated		34.07	6.1	0.67	4.06	3.01	1.06	
Amaranth	*L. Plantarum*	Control	60	20.9	5.9	0.37	5.09	1.42	0.67	6
		Inoculated		21.13	6.15	0.31	4.16	1.02	0.4	
Chamaecrista rotundifolia	*L. acidophilus*	Control	60	24.61	11.51	0.97	5.15	0.44	1.91	7
		Inoculated		26.26	15.32	0.5	4.45	1.5	1.09	
Sorghum-sudan grass	*L. brevis*	Control	40	21.43	9.02	2.56	3.51	8.27	1.78	8
		Inoculated		21.95	8.96	2.56	3.45	9.26	1.37	
		Inoculated		31.1	3.6	-	3.85	3	2.2	
Corn	*L. hilgardii*	Control	-	36.4	7.5	-	3.76	4.97	1.19	9
		Inoculated		36.2	7.6	-	3.77	4.96	1.37	
Whole-plant corn	*L. acidophilus* + *L. plantarum*	Control	45	30.8	8.16	5.37	3.51	4.44	1.14	10
		Inoculated		31.29	8.37	4.09	3.47	6.66	1.19	
Alfalfa	*L. plantarum* K KKP 593p, *L. plantarum* C KKP 788p, *L. buchneri* KKP 907p	Control	90	27.82	-	2.2	4.8	0.82	0.38	11
		Inoculated		28.25	-	3.5	4	1.65	0.4	

Notes: DM- dry matter; CP- crude protein; WSC- water soluble carbohydrate; LA- lactic acid concentration; AA- acetic acid concentration; %FM- percent of fresh matter; %DM- percent of dry matter; Reff: references; 1: He et al. (2018), 2: Hu et al. (2020), 3: Batista et al. (2022), 4: Huang et al. (2021), 5: Mu et al. (2021), 6: Zhao et al.(2022), 7: Feng et al.(2022), 8: Zhao et al.(2022), 9: Ferrero et al. (2021), 10: Jiang et al.(2020), 11: Zielińska et al. (2017).

Propionibacterium acidipropionici produces propionic acid to inhibit yeast growth (Cardoso et al., 2019) and promotes LAB growth (Mombach et al., 2018). Yeast strains (*Candida krusei* and *Saccharomyces cerevisiae*) are utilized to improve silage quality (Carvalho et al., 2016; Ghaffar et al., 2014; Wróbel et al., 2023). Recent genetic engineering has produced yeasts like *Zygosaccharomyces bailii* and *S. cerevisiae* with higher lactic acid and less ethanol (Kuanyshev et al., 2021; Mitsui et al., 2020).

Chemical and Enzymatic Additives

Organic acids

Organic acids such as citric, malic, propionic acid, and formic acid have been widely used to rapidly inhibit undesirable microorganisms such as *Klebsiella, Paenibacillus,* and *Enterobacter* (Khota et al., 2023) while enhancing aerobic stability (Gheller et al., 2021; Goeser et al., 2015; Koivunen et al., 2015). Furthermore, incorporating specific acids like malic and citric acid actively supports LAB metabolism, accelerating the onset of homofermentative pathways (Ke et al., 2021).

Cellulases and hemicellulases

Cellulases and hemicellulases enhance the availability and digestibility of water-soluble carbohydrates (WSC), increase the abundance of *Lactobacillus*, and consequently elevate lactic acid production (Du et al., 2023; He et al., 2018).

Some studies indicate that the combination of hemicellulase and *L. plantarum* enhances enzymatic hydrolysis in silage, resulting in increased glucose yield and cellulose convertibility. This synergistic action promotes a more comprehensive breakdown of cell wall structure, thereby improving fiber digestibility and nutrient availability for livestock (Passos et al., 2018; Zhao et al., 2018).

Adding lignocellulose enzymes can reduce overall lignin content and increase antioxidant capacity, thus improving in vitro fermentation and the retention of beneficial phenolic compounds (Machado et al., 2020). Proteolytic enzymes decrease protein degradation, enhancing nitrogen conversion into highly digestible peptides and amino acids (Muck et al., 2018; Nogoy et al., 2023). Amylolytic enzymes, such as α-amylase and glucoamylase, further enhance starch degradation, promote rapid acidification, and improve fermentation efficiency (Batista et al., 2022; Gandra et al., 2019). The deployment of these enzyme cocktails holds significant potential in supplying additional carbon substrates for LAB to facilitate faster and more effective pH reduction.

Water-soluble carbohydrate (WSC)

Hydrolysis of cell wall fractions inherently increases WSC availability for subsequent LAB fermentation (Li et al., 2017). Additives rich in soluble sugars, such as sucrose, molasses, and rice bran, supply epiphytic LAB with immediate fermentable substrates. Molasses is especially effective, reducing silo pH rapidly and improving overall organic matter digestibility, while rice bran enhances protein fraction and lowers the accumulation of undesirable volatile fatty acids and fermentation byproducts (Del Valle et al., 2023; Zhao et al., 2018).

Nutrient Supplement

For biomass with low protein or mineral content, nutrient supplementation during ensiling is required. Materials like urea and ammonia effectively increase crude protein, though they must be carefully dosed to avoid negative impacts on palatability (de Carvalho et al., 2018; Kung et al., 2018). Mineral additives, such as di-calcium phosphate, significantly improve animal performance, especially in dairy systems, by enhancing milk yield and lactation quality (Islam et al., 2018). Additionally, other functional compounds, including organic acid salts (potassium diformate, sodium diacetate, calcium propionate) acting as aerobic stabilizers, and calcium oxide as a chemical alkali processing agent, have also been successfully deployed to modify silage traits (Jacovaci et al., 2017; Mu et al., 2021). Absorbent additives such as bentonite and zeolite help regulate moisture and bind mycotoxins, thereby improving both silage preservation and feed safety (Driehuis et al., 2018).

Agro-industrial by-products like chitosan and molasses also serve as dual-function additives, providing fermentable substrates and antimicrobial effects (Du et al., 2023). In alignment with the pursuit of sustainable natural additive sources, bioactive compounds from local plants like Boehmeria nivea also show great potential. Ramie biomass from leaves and flowers contains active compounds (Wulandari et al., 2024) such as n-hexadecanoic acid, phytol, and neophytadiene, which possess antioxidant and antimicrobial activities. These specific characteristics could potentially be utilized as a natural additive in the ensiling process to enhance microbial stability and suppress the activity of putrefactive fungi or clostridial bacteria.

Synthesis of Additive Functions

Overall, silage additives provide multiple functions: rapid acidification, inhibition of spoilage organisms, enhanced structural carbohydrate digestibility, and nutrient supplementation. Recent studies highlight the potential of integrating tropical biomass with locally adapted additives, combined inoculants, and enzyme supplementation to address the unique challenges of silage production in hot and humid environments. Table 3 summarizes the mechanisms, impacts, and recent evidence for the main categories of silage additives.

Challenges, Future Prospects, and Economic Benefits of Using Silage Additives

Challenges

The effectiveness of additives is highly dependent on several interconnected factors, including forage type, harvesting conditions, epiphytic microbial composition, and environmental variables such as temperature and humidity (Ávila and Carvalho, 2020; Wilkinson and Rinne, 2018). The primary challenge in ensiling lies in producing high-quality, nutrient-dense feed from variable natural substrates while minimizing artificial intervention during the fermentation process.

Practical limitations in additive application encompass financial constraints for smallholder farmers and technical hurdles. These technical challenges include inconsistent inoculant performance across different crops, clostridial fermentation risks, and unfavorable biomass traits such as high buffering capacity or low water-soluble carbohydrate (WSC) content, which inherently complicate acidification (Muck et al., 2018).

Furthermore, in tropical environments, elevated humidity and ambient temperatures accelerate aerobic spoilage, necessitating higher dosages or complex combinations of additives to maintain silo stability (Liu et al., 2023; Schneider et al., 2021). Consequently, these intensive application requirements drive up production costs, further restricting the widespread adoption of advanced additive technologies among smallholders in developing countries (Ferrero et al., 2021).

Future Prospects

In tropical livestock systems, an integrated approach is needed to achieve sustainable livestock production and overcome the specific challenges of hot and humid climates. Combining conventional additives with biotechnology-based innovations enhances aerobic stability, nutrient retention, and feed safety in the long term.

Multi-omics technological approaches enable a deeper understanding of the microbial ecology of silage, thereby leading to the design of crop- and region-specific inoculants (Du et al., 2023; Guan et al., 2020).

Table 3. Summary of silage additives: mechanism, impact, and recent studies

Type of Additive	Main Mechanism	Effect on Silage	Recent Studies
Homofermentative LAB (*Lactiplantibacillus plantarum*)	Rapid production of lactic acid results in a rapid decrease in pH	Inhibits spoilage bacteria, accelerates fermentation stabilization	Arriola et al. (2021); Ferrero et al. (2021)
Heterofermentative LAB (*Lentilactobacillus buchneri*)	Acetic acid and 1,2-propanediol production	Enhances aerobic stability, suppresses yeast and mold growth	Arriola et al. (2021); Ferrero et al. (2021)
Combined LAB (homo + hetero)	Synergy: rapid pH reduction + acetic acid production	Stable long-term fermentation, suitable for tropical silages	Bernardes et al. (2018); Ferrero et al. (2021)
Organic acids (citric, malic, formic)	Decrease pH, inhibit Clostridia and enterobacteria	Improve fermentation quality and aerobic stability	Ávila and Carvalho (2020)
Enzymes (cellulase, hemicellulase)	Hydrolyze fiber can increase soluble sugars	Provide more substrate for LAB, enhance digestibility	Du et al. (2023)
Agro-industrial residues (molasses, chitosan, fishery by-products)	Extra energy source + antimicrobial effect	Increase crude protein, antimicrobial, improve stability, valorize residues	Wijayanti et al. (2022)

Metabolomic analysis of silage makes it possible to determine beneficial or detrimental metabolite profiles, while metagenomic analysis can reveal pathogenic microorganisms that produce toxic metabolites if fermentation is less than optimal. Building upon these ecological insights, genetic engineering offers a pathway to develop custom LAB and yeast strains (Kuanyshev et al., 2021; Mitsui et al., 2020).

Nanotechnology-based microencapsulation offers a promising approach to enhancing the stability and shelf life of additives. By protecting inoculants from environmental stresses during storage and ensiling, this technology ensures high microbial viability, thereby maximizing feed quality and subsequent animal performance (Ávila and Carvalho, 2020; Wei et al., 2022).

The integration of agro-industrial by-products, such as chitosan, molasses, and fishery residues, is a sustainable strategy that not only improves silage quality but also supports circular bioeconomy principles (Du et al., 2023; Wijayanti et al., 2022). Ultimately, transitioning these advanced biotechnological tools from controlled laboratory settings to field-level tropical farming systems remains the next critical milestone for sustainable feed security.

Economic Benefits

The application of additives to the silage production process provides real economic benefits by overcoming production challenges, thereby increasing feed efficiency, reducing dependence on expensive concentrate feeds, and increasing animal productivity (Wilkinson and Rinne, 2018).

Silage additives incur initial costs that vary based on product type, application level, and effectiveness in improving fermentation and nutrient preservation (Kung et al., 2018). The cost-effectiveness of silage additives also depends on factors such as crop type, harvest conditions, and management practices. For example, in areas susceptible to aerobic spoilage, additives that increase aerobic stability, such as LAB inoculants or acidifiers, can prevent losses during storage and feeding (Bernardes et al., 2018), which directly translates to a reduction in dry matter (DM) losses and preserves the financial investment made during harvests.

Although the application of additive technology increases production costs, the benefits in terms of increasing feed efficiency and reducing losses due to spoilage can provide higher economic profits, making additives a cost-effective solution for sustainable livestock systems in tropical regions (Rodriguez et al., 2024). Therefore, silage additives not only improve feed quality and farm profitability but also align with global sustainability goals by securing year-round financial resilience against seasonal feed scarcity in tropical regions.

Conclusions

In conclusion, addressing nutrient loss and aerobic instability in silage production requires a strategic combination of advanced additive technologies and Good Manufacturing Practices (GMP). Several biological, chemical, or a combination of silage additive technologies can be used to improve silage quality and ensure the availability of quality feed while supporting the sustainability of the livestock sector, particularly for optimizing underutilized tropical biomass resources.

The importance of a clearer understanding of the types, mechanisms, and functions of silage additives offers opportunities for more profitable management of silage production, but extensive research into this process is still needed. Further development and innovation in additive technology, along with advances in biotechnology, such as multi-omics, microencapsulation, and microbial strain engineering, offer promising opportunities to achieve more sustainable and resilient livestock production systems. These biotechnological advancements are expected to provide cost-effective and resilient solutions for the livestock sector. Hence, future research should prioritize comprehensive economic evaluations to validate the cost-efficiency and profitability of these additive technologies under commercial farming conditions.

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