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REVIEW ARTICLE

Transforming forage nutrition: Advances in silage additives for enhanced preservation and feed quality

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Abstract

Global demand for livestock products increases the need for high-quality fodder. However, urbanization resulted in the depletion of agricultural lands expanding the demand for food, feed and fodder. To overcome this issue, the available fodder and agricultural wastes are preserved anaerobically to feed animals. This efficient process of preserving the fodder anaerobically throughout the year is known as ensiling and the preserved fodder is known as silage. To improve the quality and longevity of silage, various additives such as microbial inoculants (bacterial inoculants, yeast), enzymes, chemical additives (organic and mineral acids), nutrients (urea, ammonia, sodium chloride, sodium di acetate) and fermentation accelerators (molasses, starchy substance, grains) are added. Addition of these additives reduces pH to below 4.2, proteolysis up to 40 %, ammonia volatilization, population of yeasts, molds and enhances fermentation, improves the aerobic stability by 2-5 days, optimizes nutrient retention and quality of silage. By supporting better livestock nutrition, silage additives increase 5 to 20% milk production, lactation period and promote beneficial microbial populations in the rumen of cattle. This review describes the usage and effectiveness of various additives that are used to enhance the silage quality in terms of storage and nutritional content.

Keywords: additives; ensiling; enzymes; molasses; proteolysis; silage; yeast

Introduction

The importance of fodder for livestock is paramount, as it directly influences their health, productivity and the safety of food products for human consumption. Livestock feed requires various nutritional factors and a balanced proportion of protein, fat, carbohydrates, minerals and vitamins (1). Adequate and high-quality feed ensures optimal growth and production efficiency, which is essential for meeting the increasing global demand for animal protein. India is currently facing a significant challenge regarding fodder availability, which is crucial for livestock feeding. The National Dairy Development Board (NDDB) estimates a shortage of green fodder (36 %), dry fodder (40 %) and feed concentrates (57 %) (2). India will face a projected 18.4 % deficit in green fodder and a 13.2 % deficit in dry fodder by 2050, highlighting significant challenges in forage availability amidst a growing livestock population of approximately 536.76 million (3). Agricultural wastes like crop residues can be utilized as livestock feed. In India about 500 - 550 metric tonnes (MT) of crop residues are generated annually. Among which wheat (110 MT), rice (122 MT), maize (71 MT), sugarcane (141 MT) and pulses (28 MT). From these residues, around 230 MT were wasted (4).

To effectively conserve the crop residues for animal feed, the ensiling process is essential. Ensiling is a preservation technique that involves the anaerobic fermentation of green fodder or crop residues to produce silage. Silage plays a crucial role in global livestock feeding systems by providing a reliable and nutritious feed source, especially during periods of forage scarcity. Silage extends the availability of forage throughout the year, addressing seasonal feed scarcity caused by climate change and natural disasters (5). Silage production involves the fermentation of forage crops, which preserves their nutritional value and extends their availability. This practice is essential for maintaining livestock productivity and supporting the growing demand for animal products worldwide. The global average percentage of livestock feed derived from silage is 10-25 %. The incorporation of silage in diets allows a reduction in the amount of concentrated feed needed, further optimizing feed costs (6). Ensiling process not only reduces feed wastage but also environmental pollution from residue burning and supports a circular agricultural economy. By improving feed availability, stabilizing prices and ensuring consistent livestock performance; ensiling offers a sustainable solution to both fodder scarcity and agricultural waste management. Utilizing silage can lower feed costs per unit of weight gain, making livestock production more economically viable (7). Techniques such as mixed ensiling with by-products can enhance the nutritional value of drought-affected crops, ensuring better feed quality for livestock (8).

Silage is preferable than hay as it has multiple harvests and does not depend on weather conditions. However, the process of silage making poses several challenges like variable quality due to air exposure, which leads to undesirable bacterial growth and poor fermentation. Poor silage has high moisture content, fewer nutrients, high contaminants and harmful microorganisms (9). Additives in silage production enhance fermentation, improve nutrient preservation and aerobic stability which refers to the silage's ability to resist spoilage upon exposure to air during storage or feeding and mitigate spoilage. They can also promote the growth of beneficial microorganisms leading to higher-quality silage, increased digestibility and better livestock performance, ultimately optimizing feed efficiency and farm productivity. They can elevate dry matter, crude protein and lactic acid contents while reducing fiber contents, pH and ammoniacal nitrogen which leads to better overall silage quality (10). This review provides an overview of the types of additives used in silage preservation, their role, mechanism of action in silage fermentation and preservation and their impact on silage quality.

Silage mechanism

Silage making can be done by growing high nutritional crops for livestock purposes and harvesting them at the right stage. In silage making process chopping the fodder into smaller particles, filling in the silos and controlling the wastages is important (11). The process of silage making is explained in Fig. 1.

Silage fermentation is a complex biochemical process that preserves forages anaerobically and converting plant sugars into organic acids (lactic acid; primarily) with the help of lactic acid bacteria (LAB) (12). LAB plays a crucial role in silage production by fermenting plant carbohydrates into organic acids such as lactic and acetic acids which helps in the reduction of pH, inhibition of spoilage microorganisms and preservation of nutrient content. LAB inoculants improve silage quality, nutritional value and shelf life by promoting rapid anaerobic fermentation. They also support rumen microbes in degrading plant metabolites during digestion (13). Recent studies have focused on functional LAB, including those that produce feruloyl esterase and possess antimicrobial, antioxidant and pesticide-degrading properties (14). These functional LAB not only help in preserving silage but also improve animal health and performance. The metabolic profiles of ensiled forages reveal several probiotic metabolites with antimicrobial, antioxidant and anti-inflammatory effects, indicating that silage could be a potential medium for delivering probiotic substances (14).

However, harmful microorganisms such as *Clostridia, Enterobacteria* and molds can cause spoilage under anaerobic or aerobic conditions, potentially reducing nutritional value and posing food safety risks (15). The processes and actions of microorganisms in the ensiling stage is elucidated in Fig. 2 (16). Aerobic stability is vital for preserving silage quality, as yeasts and molds can oxidize fermentation acids when exposed to air. Factors that influence aerobic stability include the concentration of undissociated acetic acid, silage density and porosity. To ensure optimal aerobic stability, proper management practices such as rapid ensiling, maintaining anaerobic conditions and utilization of appropriate additives are essential (17). Research has focused on developing additives that directly target harmful microorganisms, reduce mycotoxins, improve cell wall digestibility and enhance nitrogen utilization efficiency in cattle (10). Effective silage management which emphasizes rapid ensiling and maintaining anaerobic conditions, is critical for preventing undesirable microbial growth and ensuring high-quality silage. Mechanism of silage preservation and methane reduction (Fig. 3)

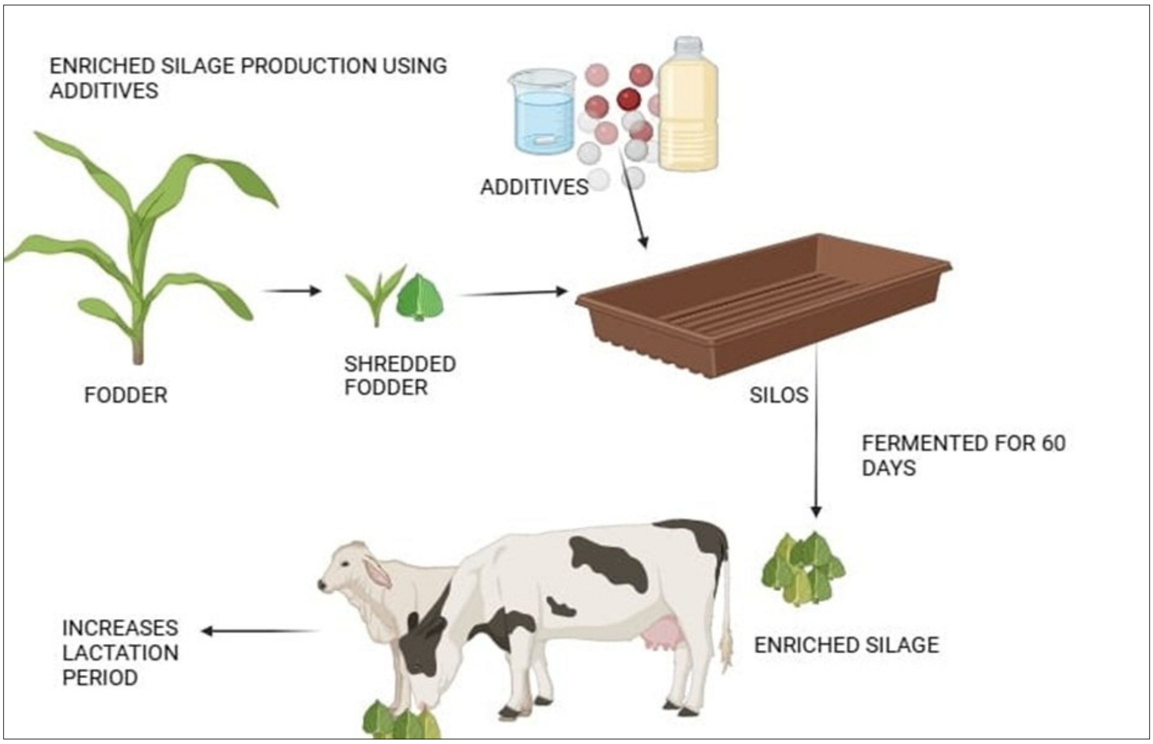

Fig. 1. Process of silage making.

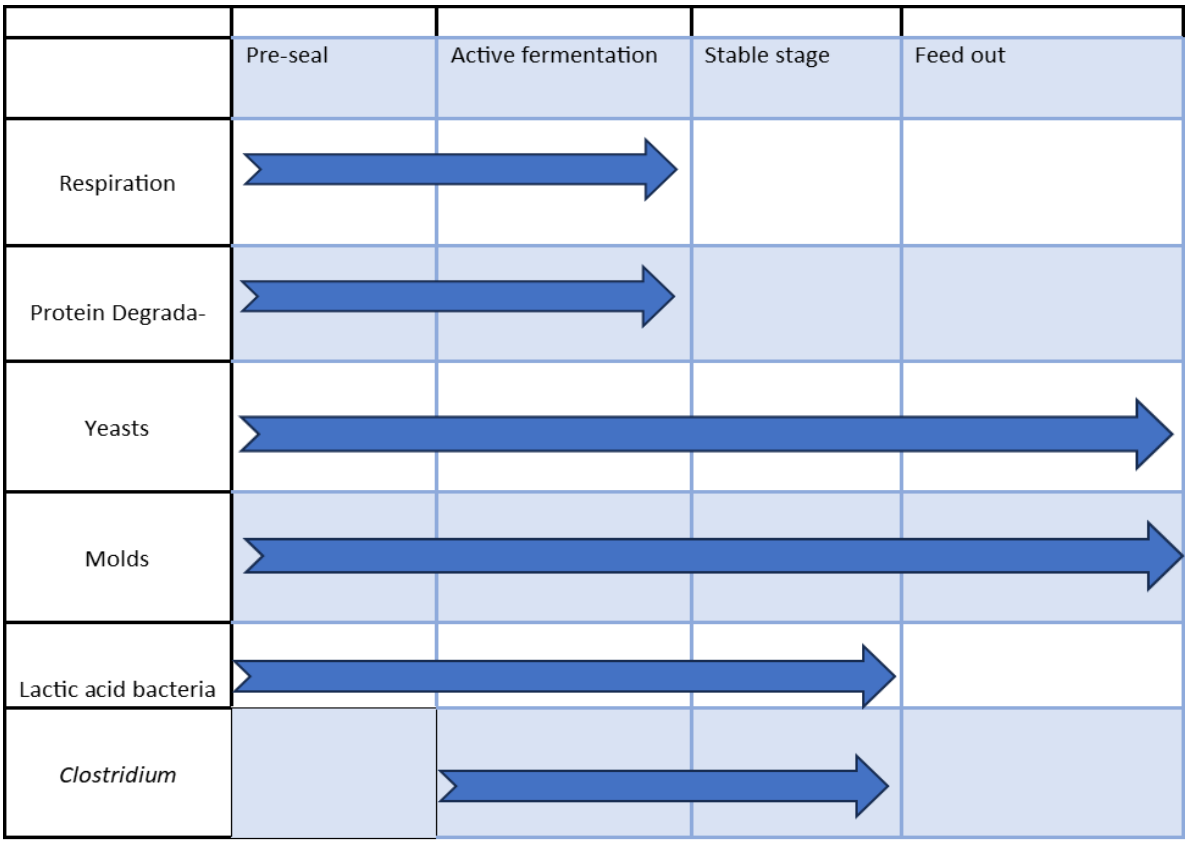

Fig. 2. Processes and action of microorganisms in ensiling stages.

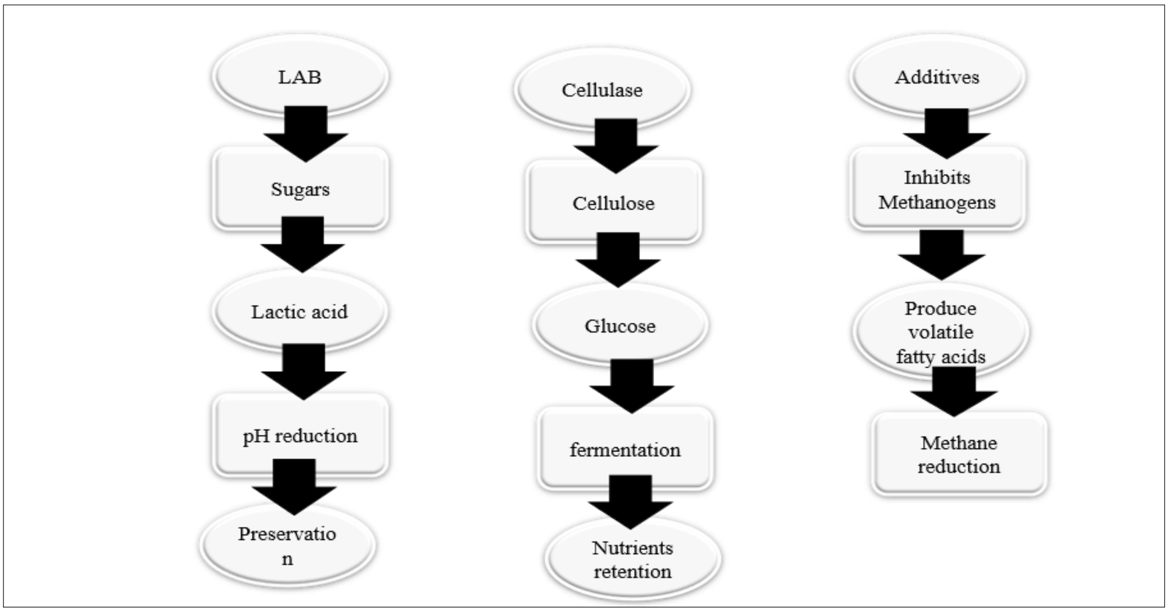

Fig. 3. Mechanism of silage preservation and methane reduction.

Additives used in silage preservation

Additives are substances introduced in the silage to improve the quality, palatability, milking ability and lactation process of animals. It also enhances the aerobic stability and nutritive value of the silage (18). Additives are used for increasing the efficacy of fermentation in the ensiling process. They are synthetic or natural and are applied as liquid or in solid form. They are applied to enhance the fermentation rate, to reduce loss of nutrients in ensiling and to augment the nutrient content. The use of additives has become popular globally, but the selection of suitable additives is important in the enrichment of silage (19). To improve the silage quality and storage ability, various additives are used (Fig. 4) and the commonly used acid-based additives, salt-based additives and fermentation stimulants are shown in Fig. 5.

Microbial inoculants and their role in silage fermentation

Role of LAB in fermentation

Several microbes are used in the production of silage process. The most prominently used microbe is the LAB *viz.*, *Lactobacillus acidophilus, Lactobacillus plantarum* and *Lactococcus lactis*, alongwith *Saccharomyces cerevisiae (Yeast)*; that have been used as the silage inoculants and this combination has produced the highest quality silage in maize (14).

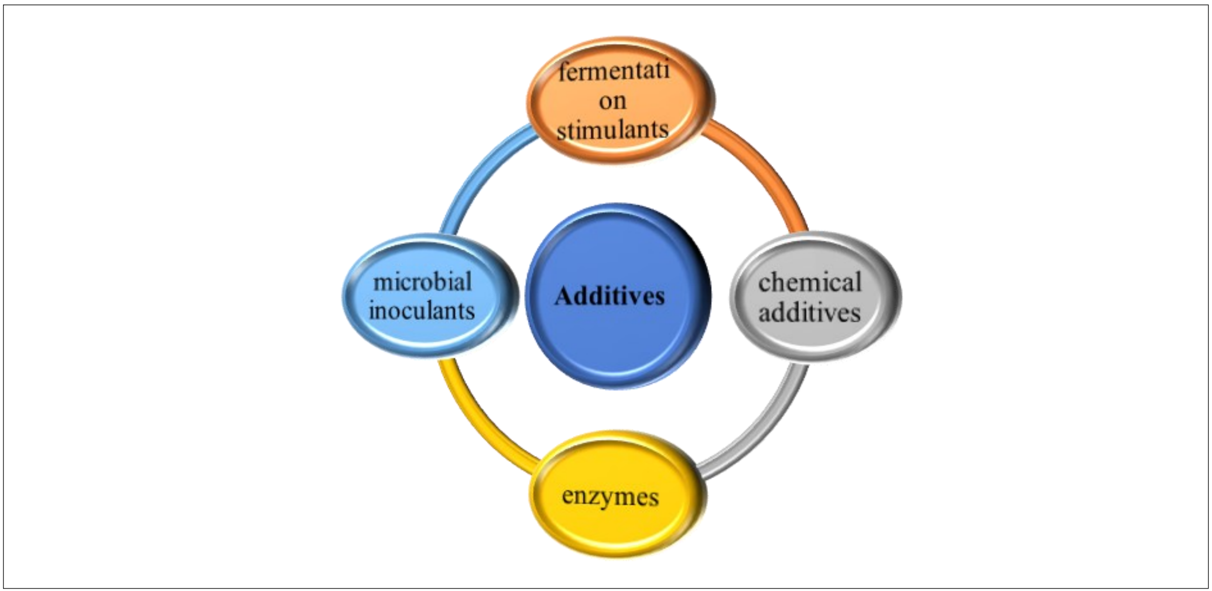

Fig. 4. Types of additives used in silage preservation.

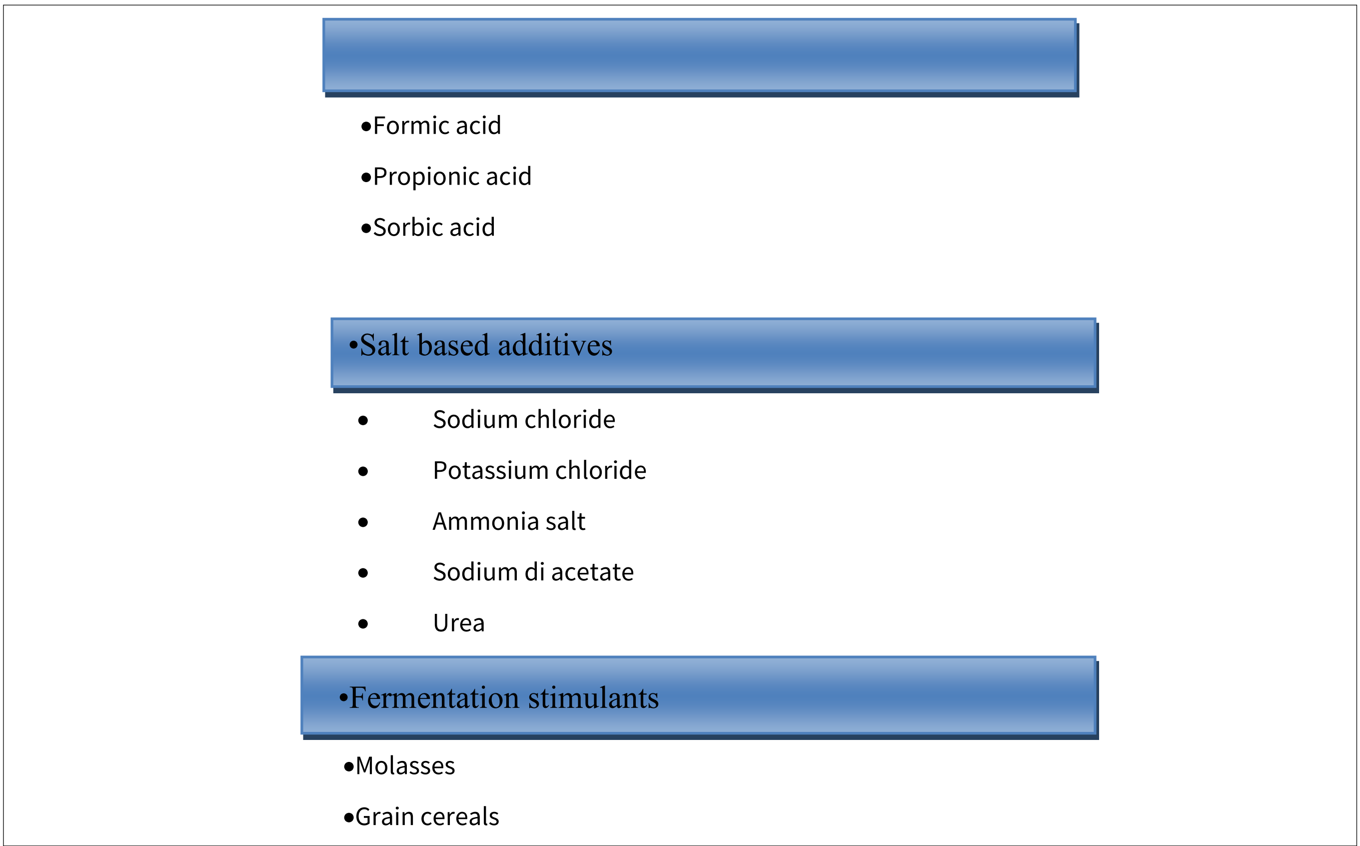

Fig. 5. Commonly used acid-based additives, salt-based additives and fermentation stimulants.

Homofermentative vs. heterofermentative LAB

Two types of LABS are involved: homofermentative LAB strains quickly suppress anaerobic pathogens, while heterofermentative species like *Lactobacillus buchneri* enhance the aerobic stability by producing acetic acid (20). The effectiveness of the homofermentative and heterofermentative LAB was studied in terms of reduction in pH, ammonia and fibre content in the alfalfa silage (21). Maize was ensiled with both homofermentative bacteria (*L. plantarum, Pediococcus pentosaceus*) and heterofermentative bacteria (*L. buchneri*) in the ratio of 1:1 concluding that the effective silage production was carried out by the homofermentative bacteria (22). The study of various strains, such as *L. plantarum (Lp), P. pentosaceus (Pp)* and *L. buchneri (Lb)* on alfalfa silage, either alone or in combination showed that Lb- and LbLp-inoculated silage increased organic acid content and water-soluble carbohydrates besides improved fermentation and carbohydrate metabolism (23).

The wheat bran fermentation process is enhanced by *L. plantarum, Lactobacillus pentosus, Lactobacillus brevis, Lactobacillus sanfranciscensis* and *Fructobacillus fructosus* (24). Aerobic stability of corn grain silage has been enhanced by the addition of *L. buchneri* (25). Effects of *Lactobacillus* strains on silage quality in different crops are listed in Table 1.

Role of yeast in silage fermentation

Many types of yeasts are useful in the ensiling process. *Pichia anomala* is the yeast that is used to prevent the growth of the molds (*Acremonium strictum, Clostridium macerans* and

Table 1. Effects of *Lactobacillus* strains on silage quality in different crops

Lactobacillus sps.	Crops used	Advantages	Limitations	References
L. buchneri A KKP 2047 p (LB), L. reuteri M KKP 2048 p (LR), L. plantarum K KKP 593 p (LPk), L. plantarum S KKP 2021 p (LPs), L. fermentum N KKP 2020 p (LF)	Corn	Reduces the aflatoxin B1 and ochratoxin toxicity in the silage.	Successful in laboratory level, not ensured with animal safety.	(26)
L. brevis SDMCC050297 and *L. parafarraginis SDMCC050300*	Corn stover	Improves the quality of silage.	Reproducibility was seen only in early and late stages of ensiling process.	(27)
L. plantarum LpM15 and *L. fermentum* LfM1	Maize, oats, lucerne and sorghum	Former enhances cross fermentation ability and efficiency, later strengthens the maize silage.	Combination effect of these strains yet to be studied.	(28)
*L. buchneri (*LS-31-1-4*), L. brevis* (LS-55-2-2) and *Leuconostoc citreum* (LS-70-6-1)	Alfalfa	*L. buchneri* improves dry matter production about 97 % and other two LAB increases the aerobic stability of silage against yeast and bacteria.	Requires more inoculum.	(29)
L. buchneri A KKP 2047 p (LB*), L. reuteri* M KKP 2048 p (LR*), L. plantarum* K KKP 593 p (LPk*), L. plantarum S* KKP 2021 p (LPs*), L. fermentum* N KKP 2020 p (LF)]	Corn	Reduced the aflatoxin, ochratoxin, other microbial loads in silage.	Requires more inoculum.	(26)

Cryptococcus wieringa), reduce the count of the Enterobacteriaceae microbes, enhance the population of LAB for the effective production of silage from barley and inhibits the toxicity of the *Aspergillus* fungi (30). The study on yeast genera *Saccharomyces* showed the effectiveness of the silage preparation by enhancing aerobic stability and production of low ethanol concentration (31). *Streptococcus* strains are equivalent to LAB in fermentation, which helps in increasing microbial activity in the rumen of animals and enhances the fermentation (32). Yeast treatment in silage has shown promising improvements in nutritional quality and fermentation efficiency. The application of *Saccharomyces cerevisiae* Hansen, *Humicola grisea* var. *thermoidea* and *Candida glabrata* to rice straw silage significantly increased crude protein content and the presence of single-cell protein-producing microorganisms, while simultaneously lowering pH and reducing the growth of spoilage organisms (33). Similarly, combining cassava pulp with rice straw and treating it with liquid brewer's yeast enhanced the ether extract and crude protein levels and reduced both pH and fiber content. However, applying brewer's yeast at higher concentrations led to increased fermentation deterioration, indicating the importance of proper dosage (34). Furthermore, the use of Crabtree-negative yeasts, such as *Pichia kudriavzevii* and *Candida tropicalis*, in rice straw silage improved digestibility by 6.9 %, enhanced ruminant microbial populations and increased nutrient content and milk protein yield when compared to Crabtree-positive yeasts (35)

Enzymes in silage fermentation

Enzyme-based silage additives include cellulases, hemicellulases, xylanases, amylases and pectinases. Enzymes are used as additives that convert fibre to sugar and these sugars are consumed by LAB to aid in fermentation. These enzymes are added at the last stage of fermentation in order to increase the nutrient concentration, palatability and to reduce the non-degradable fibre in silage. At p^H 4.5 and a temperature of 500 °C, enzymes increase fermentation, lower acid production and ammonium content in fibre (36). The role of enzymes in enhancing the silage quality and fermentation efficiency is highlighted in Table 2.

Amylase enzyme is used to convert starch into sugar, whereas cellulase, hemicellulases, xylanases and pectinases degrade cell walls into sugar; which is utilized by silage-making bacteria (10). *Alpha amylase, endo-1,4-β-glucanase* and *endo-1,4-β-xylanase* enzymes derived from different strains of *Bacillus, Aspergillus* and *Trichoderma* improved dry matter intake by 14 %, milk yield by 10 %; rendered safe for animal consumption, even though some fungal strains may be toxic to animals (37). Sorghum straw silage with *cellulase, xylanases* and extrusion puffing technique resulted in improved sorghum straw silage fermentation by enhancing silage quality, digestibility and nutritive value through bacterial community modulation, especially increasing *Alcaligenaceae* dominance. *Xylanase* outperformed cellulase by increasing soluble sugars and promoting microbial growth (38). The assessment of alfalfa silage treated with cellulase, α-α-galactosidase, or their combination with *Lactobacillus plantarum* revealed notable improvements in fermentation quality and nutritional value. These treatments significantly lowered pH and ammonium-N levels while increasing populations of beneficial lactic acid bacteria (LAB), particularly *Lactobacillus* and *Pediococcus* species. Additionally, the treatments enhanced crude protein content and reduced neutral detergent fiber (NDF), resulting in improved overall silage quality (39). Enzyme inoculants (xylanase, β-mannanase, glucanase) and bacterial inoculants (*Lactobacillus, Aspergillus, Candida, Pediococous, Bacillus*) applied in reed, rice and corn straw improved fermentation, increased crude protein and lactic acid, reduced fiber and pH as well as altered the microbiome by promoting beneficial bacteria. Double doses of *Bacillus subtilis* and glucanase optimized silage quality (40). Perennial ryegrass treated with the enzymes hemicellulases and cellulases showed improved silage quality by significantly reducing cellulose, acid detergent fiber (ADF) and neutral detergent fiber (NDF) contents. The enzymatic treatment also enhanced the population of lactic acid bacteria (LAB) and increased microbial activity in the rumen of animals, contributing to better digestibility and fermentation efficiency (41).

Table 2. Role of enzymes in enhancing silage quality and fermentation efficiency

Enzyme	Silage	Mechanism	References
Proteases	Corn	Boosted soluble protein, ammonium- N, starch digestibility and enhanced ruminant starch digestion.	(42)
Amylases	Corn	Enhanced LAB, ammonium- N, lactic and butyric acid content.	(43)
Cellulases+ Xylanases	Alfalfa, wheat, rice straw, oat	Increased acetic acid and crude protein content, enhanced dry matter content, reduced cellulose content and increased fermentable sugar content.	(44) (40)
Cellulases+ hemicellulases+ pectinases	Pea, wheat	Reduced neutral detergent fiber, acid detergent fibre, yeast and molds, increased CO_2.	(45)

Chemical additives in silage fermentation

Role of acid-based additives

The addition of formic acid (4.6 l/t) and formalin (6.3 l/t) to the silage has impeded the growth of *Clostridium* in the silage making. The digestibility of the silage made with formic acid as an additive was higher than the silage made with formalin (46). Addition of formic acid along with LAB to the mixture of sugarcane top and Napier grass has improved the fermentation quality both *in vitro* and *in vivo* in the rumen of cattle (47). A study evaluated the effect of 2 l/t propionic acid on whole-plant maize silage, reduced NH3-N, altered organic acid ratios, improved aerobic stability by 40 hrs and accelerated yeast growth during fermentation (48). Increasing the shelf life of the corn grain silage with the treatment of the sorbents, propionic acid and myco-flake has resulted in an increase in storage ability from 30 to 60 days (49). Addition of sorbic acid (0.9 -1.0 kg/t) to the silage enhances the quality and quantity of ensiling, improving the aerobic stability of the silage (50). Sorbic acid (0.1 %) and molasses (1.0 %) M was added to the Cumbu Napier grass, which boosted the production of the high- quality silage for off-season feed to the cattle (51). Usage of sorbic acid and potassium sorbate has enhanced the aerobic stability of the silage by reducing the volatilization of ammonium alongside the population of yeasts and molds in the silage (52). When heterofermentative LAB is inoculated into the silage, the aerobic stability is enhanced due to the production of acetic acid. This acetic acid produced will inhibit the growth of other spoilage microbes present in the silage (53). Ethanol was oxidized to acetic acid by the acetic acid bacteria to enhance the quality of the silage (54). Hydrochloric acid (2 l/t) when added to the substrate undergoing ensiling process, reduces the growth of other microbes besides the pH and increases the growth of LAB by improving the silage quality (55). Sulphuric acid (5 l/t) is the most important preservative used for prevention of the spoilage microbes. The usage of sulphur treated silage has less copper accumulation in the liver of the cattle being fed (56). Conocarpus is non-toxic plant; when treated with sulphuric acid and molasses becomes the efficient feedstock for ensiling process, intensifying the digestibility of the silage (57).

Role of salt - based additives

When sodium chloride (NaCl), 40 kg/t is added in the ensiling process, it prevents the growth of anaerobic microbes like *Clostridium* that affect the growth of LAB, causing poor-quality silage. NaCl does not improve the quality of silage directly by addition; it stops the growth of unwanted anaerobic microbes (58). Potassium chloride (38.1 kg/t) was added to alfalfa prior to the ensiling process, which resulted in a reduction of acid production, lowering pH, hindering harmful microbial growth and deprived of affecting the proteolysis activity. Thus, the addition of potassium slows down the process of proteolysis without affecting LAB culture growth (58). Ammonium (3 kg/t) added as an additive to the silage did not affect the growth of LAB, but it increased the pH impeding the growth of yeast and other anaerobic bacteria that reduce the production of lactic acid at later stages. When silage is exposed to oxygen, there is no growth of the yeast and anaerobic microbes, thereby enhancing the aerobic stability of the silage (59). Excessive application of ammonia results in the poor fermentation of the silage. Application of liquid ammonia is always preferable to the gaseous application (60). Alfalfa silage treated with sodium diacetate (5 g/kg) resulted in enhancing fermentation, chemical composition, aerobic stability, water soluble carbohydrates and N peptides as well as reduced the pH, harmful microbes and dry matter loss (61). Sodium diacetate (6 g/kg) in rye silage was assessed to increase fermentation, digestibility and aerobic stability along with reduced fibre content and minimized spoilage (62). The combination of sodium benzoate, potassium sorbate and sodium nitrate impeded the production of ethyl alcohol and increased the aerobic stability of the silage fermentation process (63). The addition of formic acid, ammonium formate, propionic acid, benzoic acid and ethyl benzoate in silage preparation improved the milking ability in cows (64). An experiment on wheat straw silage with urea and molasses resulted in increased crude protein and pH with reduced fiber content (65). Urea at 1.5 % resulted good colour and odour, whereas urea at 3 % resulted in dark silage and ammonia odour. Yunus (66) has concluded that while 5 % molasses and 0.6 % urea are added, it enhances the nutritive and preservation quality of silage. Urea is used to improve the aerobic stability and nutritive value of the corn silage when inoculated using *L. buchneri* (67). Adding probiotics (0.02 - 0.05 %), urea (5 %) and molasses (5.5 - 6 %) to barley and Malva grass silage improved physical qualities, reduced pH to 4.5 for optimal ensiling, decreased fiber content and enhanced the silage's nutritive and storage quality (68). Various roles of chemical additives in silage preservation and quality enhancement are explained in Table 3.

Fermentation stimulants in silage fermentation

Carbohydrates are essential for the fermentation of the fodder and forage grasses. The various sugar sources generally include the molasses and grain cereals. Let us discuss the importance of molasses and other starchy substances used to enhance the process of silage. Molasses is used as an effective and cheaply available additive for the ensiling process. Adding LAB (L) and molasses (M) to native grass silage improves fermentation,

Table 3. Roles of chemical additives in silage preservation and quality enhancement

Chemical additives	Additives	Concentration	Role	Reference
Acid based				
	Formic acid	4. 6 l/t	Reduces the growth of harmful bacteria, increases lipid metabolism, antibiotic synthesis.	(69)
	Propionic acid	2 l/t	Increases the growth of β-carotene producing bacteria.	(70)
	Sorbic acid	0.9-1.0 kg/t	Increases the aerobic stability, reducing volatilization of ammonia, increases the water-soluble carbohydrates.	(51)
	Acetic acid	3 l/t	Impede the growth of spoilage microorganism, yeast and molds.	(61)
Salt based				
	Sodium chloride	40 kg/t	Improved fermentation and reduce pH, neutral detergent fiber, zearlenone and spoilage aerobic bacteria.	(70)
	Potassium chloride	38 kg/t	Increased blood proton concentration, altered the k and mg levels in plasma.	(70)
	Ammonia salt	3 kg/t	Buffering effect, enhance aerobic stability.	(59)
	Sodium diacetate	7 kg/t	Reduce the top spoilage (fungi).	(71)
	Urea	6 kg/t	Enhance dry matter content, crude protein degradability and organic acid production.	(72)

increases nutrients and reduces harmful microbes. This combination enhances quality more effectively than individual treatments (62). Application of molasses and fibrolytic enzyme improved the efficiency of ensiling process. The addition of sugars enhanced the lactic acid production and reduced the volatilization of ammonia (50). The sugar beet pulp, molasses (5 %) along with sainfoin (5 %) were added to fodder for enhancing the dry matter production, milking period and nutritional status of the milk in dairy cows (74). The addition of molasses and barley has improved the quantity and quality of silage made with artichoke. Also, the addition of molasses has reduced the potassium, protein and fibre content in the artichoke byproduct (75). When common reed (*Phragmites australis*) was treated with 10 % molasses, increased the aerobic stability of the silage, lactic acid production, bacterial count, reduced dry matter loss and contaminants in the silage. The effectiveness of the silage has increased when the seaweed is treated with 10 % molasses (76). Leucaena silage treated with 4% molasses showed improved fermentation quality and increased palatability, leading to better acceptance and utilization in the rumen of cattle. The addition of molasses enhanced the energy content and supported favorable microbial activity during ensiling, contributing to higher feed intake and nutritional value (77). Molasses in combination with other additives gives better results; these are represented in Table 4. Adding sugarcane molasses (1–3 %) improved alfalfa silage fermentation by lowering pH, increasing lactic acid, enhancing nutrient preservation, inhibiting harmful microbes, reducing ammonia and improving taste. The 3 % molasses treatment achieved the best quality and long-term preservation in alfalfa (78).

Lucerne when added with sugar, aided in increasing the population of homofermentative LAB, reducing the pH and loads of other harmful bacteria (84, 85). Potato chips that are added to the silage preparation process as the source of sugar enhanced the fermentative process of the silage and reduced the pH, ammonia gas emission and carbon dioxide. It has also led down the population of yeasts and other contaminant microbes (86). Addition of grains to the silage reduces the feeding of grains separately to the cattle. It also adds the starchy content which enhances the silage fermentation process. Ensiling process with rehydrated ground corn grain with LAB has improved the aerobic stability of the silage (59). Barley grains are added to the silage, enhancing the aerobic stability of the silage. The addition of barley did not affect the rumen fermentation but has changed the bacterial constitution of the rumen and increased the milk's nutritional content (87). Addition of grains in the silage process did not increase the milking but enhances ensiling (72).

Challenges in silage fermentation by additives

The effectiveness of additives also depends on factors like the natural microbial content of the forage, harvesting conditions and sugar levels (72). In hot climates, high temperatures can decrease crop yield and quality, promote undesirable fermentations and accelerate aerobic spoilage. In contrast, cold climates complicate crop selection and hinder effective microbial fermentation (88). Additives can result in variable

Table 4. Influence of molasses combination on silage fermentation efficiency and preservation

Silage	Molasses combination	Action	References
Soya bean	Molasses 2 % + LAB 2 %	Improved fermentation, suppressed *Clostridia* and *Enterobacter*	(78)
Cuba OM 22	Molasses + whey 50 mL/Kg	Reduced Neutral Detergent Fibre, pH, increased non fibre carbohydrates and improved forage conservation	(79)
Sorghum	Molasses 5 % + epiphytic LAB 1 %	Shows low volatile nitrogen and high v- score indicators of good quality	(80)
Baled alfalfa	Molasses + LAB	Increased fermentation quality, digestibility and protein preservation	(81)
Wilted alfalfa	Molasses + hetero and homofermentative LAB	Increases acetate, propionate and improved aerobic degradability.	(82)
Total mixed forage silage	Molasses 4 % + 0.1 % LP + 0.1 % *Trichoderma viridae*	Reduced pH (3.6), ammonia (0.453 %) and increased lactic acid (4.28 %)	(83)

fermentation outcomes. For example, LAB may not always produce the expected levels of acid, affecting pH and nutrient preservation (89). The presence of heterofermentative bacteria (*L. brevis*) can lead to higher acetic acid levels and lower lactic acid, which may not be ideal for all types of silage (87). The addition of various additives such as malic acid (MA), glucose (GL), cellulase (CE) and *B. subtilis* (BS) can significantly alter the bacterial populations in silage, sometimes favouring harmful microorganisms (Proteobacteria) over beneficial ones (Firmicutes) (90). For example, adding organic acids like propionic acid can shift microbial dynamics, affecting fermentation efficiency and the stability of silage (91). Additives meant to enhance aerobic stability may not always work as intended. In some cases, treatments can encourage yeast growth, leading to spoilage. Achieving the right balance between controlling harmful microbes and promoting beneficial fermentation is crucial and improper use of additives can disrupt this balance (87).

Future thrust

Future research in silage preservation should focus on a multifaceted approach to enhance efficiency, sustainability and safety. A key area of exploration is the development of natural and environmentally friendly additives, such as plant-based acids or probiotics that reduce reliance on chemical preservatives while improving fermentation quality. Biotechnology innovations including genetically modified LAB, create opportunities to optimize fermentation processes and enhance silage stability. Despite positive outcomes in controlled settings, a notable gap exists in the lack of large-scale field trials particularly on LAB-enzyme combinations under tropical climatic conditions where silage faces unique challenges such as higher ambient temperatures and rapid spoilage. Furthermore, research into improving aerobic stability, which is crucial for silage quality after opening, should prioritize understanding the microbial interactions and identifying the additives that inhibit spoilage and mold growth without compromising nutritional content. Enzyme-based additives, particularly those that improve fiber degradation and nutrient digestibility require further optimization for diverse silage types as well as their long-term effects on animal health and feed efficiency, which need to be thoroughly investigated. Cost-effectiveness and economic studies alongside large-scale on-farm trials are necessary to assess the practicability of these additives for farmers. Moreover, nanotechnology holds promise for enhancing the stability, bioavailability and efficacy of silage additives, though further research is needed in this emerging field. Finally, studies on the safety and environmental impacts of these additives including the potential for toxic residues or contamination are crucial for ensuring the broader adoption of sustainable silage preservation practices.

Conclusion

Silage made from fodder crops ensures the availability of feed for cattle throughout the year. Enriching this silage using various additives boosts the quality, longevity and nutritional status. Additives such as bacterial inoculants, enzymes, yeast, inhibitors and chemical preservatives are added to optimize ensiling process, reducing the spoilage and improving the digestibility of silage. Among all the additives, microbial inoculants play a major role in ensiling process by enhancing the aerobic stability and palatability of the silage. In conclusion, additives play a crucial role in the production of enriched silage. Thus, proper selection and integration of various additives based on the raw material, moisture content, pH, inhibitors etc. helps in the production of potential silage for the improvement of lactation period in cattle.

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Authors' contributions

USPKR carried out the tasks of writing, review & editing, alongside the formulation of the original draft. TS carried out writing, critically reviewing & editing along with conceptualization and supervision. NS, KRVS, MT critically reviewed and provided suggestions. All authors read and approved the final manuscript.

Compliance with ethical standards

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