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Technological advances in maize-based fodder systems: Quality improvement, digestibility optimisation and feed security

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Abstract

India's livestock sector faces a significant challenge in meeting the nutritional requirements of its growing animal population, with current estimates showing shortages of 30.65 % in green fodder and 11.85 % in dry forage. Maize (*Zea mays* L.) offers a practical solution to this problem because of its rapid growth, high biomass production and excellent suitability for preservation as silage. Genetic improvement programs have developed varieties with better protein profiles, including quality protein maize containing 30–55 % more lysine and tryptophan than ordinary maize. Breeding efforts using marker-assisted selection (MAS) and genome editing techniques like CRISPR-Cas9 have successfully targeted genes responsible for lignin production, resulting in plants with lower fibre content and improved digestibility. Field management practices play a critical role, with optimal fertiliser application, zinc (Zn) supplementation and intercropping with cowpea contributing to higher protein content while reducing difficult-to-digest fibre fractions. Post-harvest treatments are equally important. Turning maize into silage with specific bacterial inoculants such as *Lentilactobacillus buchneri* extends aerobic stability by 71–250 hr and reduces dry matter losses during storage. For maize stalks, treating them with mild alkali solutions or fibrolytic enzymes can increase digestibility from around 41 % to nearly 55 %. When livestock consumption improves maize fodder, results show clearly in their performance, with dairy cows producing up to 13.7 % more milk and growing animals converting feed more efficiently. This review synthesises recent advances in genetic improvement, agronomic management, post-harvest technologies and silage innovations aimed at improving the nutritional quality, digestibility and utilisation of maize fodder. Bringing together better varieties, sensible field practices and effective preservation methods offers a practical path toward reducing the fodder shortage while supporting livestock productivity.

Keywords: aerobic stability; biomass pretreatment; feed efficiency; forage preservation; genetic improvement; silage inoculants

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1. Introduction

Livestock plays an important role in agriculture and is regarded as the foundation of Indian farming for maintaining livelihoods, nutrition, environmental balance and agricultural development. India has the largest livestock population globally, which steadily increases annually. Accordingly, the demand for their feed and nutritional needs is rising at a similar rate (1–3). Ensuring feed availability during resource-scarce periods is essential for efficient livestock management (4). The fodder crops cultivated are noncommercial and produced on degraded and marginal lands with minimal inputs.

According to Indian Grassland and Fodder Research Institute (IGFRI) Vision 2050, India experiences a shortfall of 30.65 % in green fodder and 11.85 % in dry forage, which has been recognised as a significant factor contributing to low livestock productivity (5, 6). Inadequate nutritional support during periods of scarcity leads to adverse effects on the health of dairy animals, including weight loss, impaired fertility, reproductive issues, reduced breeding coverage and decreased draft power (6). Consequently, livestock primarily rely on straws, stover, husks and crop byproducts as their main feed sources (7), which typically contain lower levels of essential nutrients, particularly protein and energy. The combination of these challenges and the increased demand for livestock products due to rapid urbanisation and a surging human population highlights the need to improve the nutritional value and utilisation of crop residue (3).

Maize (*Zea mays* L.) thrives well in different climatic conditions (3). Maize is among the most extensively researched cereal crops owing to its rich genetic diversity and broad adaptation (8). Maize is grown in more than 170 countries worldwide on an area of about 193.7 million hectares, with an annual production of about 1147.7 million tonnes and an average productivity of 5.75 t/ha (9). Maize is used worldwide for feed (61 %), food (17 %) and industrial purposes (22 %), indicating its significant role in the global agricultural economy (9). India is amongst the major maize-producing countries in the world, ranking fourth in area under cultivation and seventh in production, contributing nearly 4 % of the area under maize cultivation to the world and 2 % of the total world production.

In India, maize is the third most important food crop, with a production of 356.73 lakh tonnes in 2023–24, cultivated over approximately 108.87 lakh hectares (Directorate of Economics and Statistics, Government of India (GOI). Among various non-leguminous forage crops, maize is regarded as an excellent forage option due to its rapid growth, high palatability of biomass and its ability to enhance both body weight and milk quality in cattle, attributed to its superior nutritional content (10) and is most appropriate for silage production due to its high levels of soluble sugars and starch in the fodder (11). The nutritional value and digestibility of mature maize stover have been found to be significantly limited by the lignification of cell walls. Accordingly, the best fodder preservation technique should reduce nutrient losses, increase digestibility, maintain fermentable carbohydrates and ensure that high-quality fodder is available year-round. By preserving nutrients through anaerobic fermentation and enabling a steady supply of nourishing feed for dairy cattle, silage production satisfies these requirements (4). The nutritional value of silage is influenced by various preharvest factors of forages, including the physical structure and the chemical composition of plants. Researchers have developed a number of pre-treatment strategies to enhance nutritional content and release its nutritional potential. These include physical, chemical and biological treatments (3). Quality of maize forage before and after harvesting is greatly affected by appropriate harvesting strategies and choice of genotypes. Consequently, future breeding should be geared towards developing hybrids that have good forage production capacity, improved digestibility and desirable traits such as good grain to stover ratio (e.g., dual purpose maize and QPM300) (12). To optimise resources and improve logistics, maize fodder can be transformed into value-added products, including densified feed blocks aimed at nutrient enhancement and preservation, which are formulated as complete mixed diets (12, 13). This review synthesises recent advances in genetic improvement, agronomic management, biomass pre-treatment, silage technology and post-harvest innovations aimed at improving the nutritional quality, digestibility and utilisation of maize fodder.

Genetic improvement for nutritional quality

Classical breeding has substantially improved forage yield and biomass production, leading to the development of high-yielding cultivars such as African Tall that support better ruminant nutrition (14). Recent molecular breeding approaches have expanded genetic improvement by targeting forage quality traits. The high heritability of traits such as crude protein, acid detergent fibre, dry matter yield and green forage yield indicates that these qualities can be effectively enhanced through selection, whereas traits with moderate heritability may require more advanced breeding approaches (15).

Modern genomic tools, including Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR)-Cas9, RNA interference (RNAi), genome-wide association studies (GWAS), haplotype breeding and marker-assisted selection (MAS), have accelerated the enhancement of maize feed quality by focusing on genes involved in lignin production and locating genomic areas linked to nutritional qualities and digestibility (8, 14, 16–19). CRISPR-Cas9 was used to disrupt genes involved in lignin biosynthesis such as cinnamyl alcohol dehydrogenase (CAD) and caffeic acid o-methyltransferase (COMT), which improves animal feed digestibility and nutritional quality (16). While low lignin levels achieved through genome editing enhanced digestibility, excessive lignin reduction can compromise plant structural stability and stress tolerance, indicating the need to balance feed quality with crop performance (16, 17). Analysing haplotypes of genes involved in lignin biosynthesis, like phenylalanine ammonia lyase (PAL), aids in choosing parental lines for enhanced forage quality (18). Genome-wide association studies makes it easier to identify single nucleotide polymorphism (SNP) markers associated with nutritional traits, including crude protein, fibre content, digestibility and cell wall composition, by using global germplasm collections (19). The efficiency of choosing superior genotypes has been improved by GWAS and MAS, but their efficacy depends on the availability of a variety of germplasm and validation in various environments (8, 19). Recent maize cultivars and hybrids with improved forage traits are listed in Table 1.

Agronomic management for nutritional quality

Selection of suitable cultivars, together with optimised crop management, plays a crucial role in improving both forage yield and nutritional quality of maize. When compared to conventional cultivars like African Tall, the cultivar J-1006 has shown better agronomic performance and green fodder yield, indicating that varietal development is still an important approach for improving fodder productivity (21). Crop management practices, including timing of sowing, fertiliser management, irrigation quality, cropping techniques and harvest stage, significantly influence cultivar performance. Timely or early sowing improved crude protein content and overall forage quality under the experimental conditions, whereas the high salinity in irrigation water resulted in stunted root growth, reduced nutrient uptake, leaf chlorosis and lower dry matter yield

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(22, 23). Seed rate of 60 kg ha^{-1} combined with 125 % recommended dose of fertiliser (RDF) improved green fodder and dry matter yields, along with crude protein, ether extract and ash contents, while lowering fibre content (24, 25).

Balanced nutrient management is equally important for achieving both high yield and superior forage quality. Adequate nitrogen (N) fertilisation, integrated nutrient management involving organic and inorganic sources, higher fertiliser doses under appropriate conditions and zinc (Zn) supplementation have consistently enhanced green fodder yield, dry matter production, crude protein content and nutrient uptake while reducing fibre fractions such as neutral detergent fibre (NDF), acid detergent fibre (ADF) and acid detergent lignin (ADL) (24, 26, 27). Intercropping maize with cowpea suppresses weeds and improves resource-use efficiency, demonstrating that sustainable agronomic practices can reduce dependence on chemical inputs (28). The responses to improved management practices are influenced by soil type, climate and genotype, indicating that location-specific recommendations are more appropriate than generalised management strategies. Harvesting maize at the optimum physiological stage, such as the milk line stage, is essential to balance biomass yield with digestibility and silage quality, emphasising that both genetic improvement and agronomic management are required to maximise feed value (4, 29).

Nutritional management for improved nutritional quality

Nutrient management practices play a central role in improving the nutritional quality and digestibility of fodder maize by enhancing biomass production, protein accumulation and nutrient composition (3). According to previous research, the application of 75 % RDF combined with plant growth-promoting rhizobacteria (PGPR) and panchagavya sprays in maize cv. J-1006 significantly improved fodder yield and nutritional quality while reducing fibre content (30). Foliar applications of 2 % urea and 0.5 % Zn at 65 days after sowing (DAS) augments components such as crude protein, ether extract, total ash, carbohydrate content and dry fodder yield compared with the control (31). A basal dose of 20 kg/ha zinc sulphate ($ZnSO_4$) increases Zn levels and uptake, plus crude protein, ether extract and ash yields, all with less fibre for richer fodder value (21). The application of potassium (K)-solubilising bacteria, combined with the recommended K dose under raised-bed cultivation, promotes higher biomass production, chlorophyll content, nutrient uptake, plant vigour and delayed senescence (32). This synergistic approach enhances nutrient availability and uptake, thereby contributing to robust plant development and sustained photosynthetic activity throughout the growth cycle. Intercropping maize and cowpea in 1 : 1 row ratios enhance the yields of crude protein and enriches the loads of both macro and micronutrients, ensuring a balance between output and the quality of feed (33). Nutritional quality can be further enhanced through integrated crop and silage management. Intercropping maize with cowpea (1 : 1 rows) increased crude protein yield by 20.4 % and improved macro- and micronutrient availability compared with sole maize (34), while fertilisation with N, selenium (Se) and Zn enhanced fodder yield, digestibility, protein concentration and micronutrient content (35). An optimal N-to-phosphorus (P) ratio of 150 : 75 significantly improves green fodder yield, crude protein and ether extract content while reducing NDF and ADF (4). The judicious use of nano fertilisers, including 1 % nano urea plus and 100 ppm nano zinc oxide (ZnO), in combination with suggested fertiliser amounts, significantly boosts plant height, the number of leaves and both green and dry fodder production, while also enhancing forage quality by increasing crude protein, ether extract and total ash content while lowering undesirable fibre components (31). Nanotechnology, particularly through nano Zn application, demonstrates significant potential for biofortifying maize fodder, leading to improved forage productivity and nutritional quality by enhancing Zn uptake and reducing fibre content (36). Table 2 summarises the effects of major nutrient management strategies on the nutritional quality and digestibility of fodder maize.

Table 1. Recently released fodder maize cultivars and their forage performance

Sl. No.	Name of the cultivar	Nature of cultivar	Year of release	Pedigree	Method of selection	Special attributes	GFY (q/ha)	DMY (q/ha)	References
1	GFM-1	Composite variety	2024	Composite of indigenous high-biomass genotypes	Mass selection	High green forage yield, adapted to Gujarat	610.0	135.0	(20)
2	AFH-7	Hybrid	2024	Single-cross hybrid	Hybridisation	High fodder and digestibility, multi-cut potential	640.0	145.0	
3	DFH-2	Hybrid	2025	Single cross inter-subspecies hybrid, a cross between cultivated maize (*Zea mays* L.) and its wild ancestor, teosinte (*Zea mays* subsp. *parviglumis*)	Hybrid breeding	Excellent plant vigour, tolerance to foliar diseases	665.0	152.0	
4	J-1009	Composite variety	2025	Improved derivative of J-1006	Modified recurrent selection	Enhanced biomass, lodging resistance, better digestibility	525.0	118.0	

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Table 2. Nutrient treatment effects on fodder maize nutritional quality and digestibility

Nutrient treatment/scenario	Key nutritional quality response in fodder maize	References
Optimum N with Zn (soil or foliar $ZnSO_4$) vs without Zn	$ZnSO_4$ (soil or foliar) raised CP to 9.0 %, total ash to 7.2–7.4 % and EE to 2.1 % compared with lower values in the control, indicating better protein and energy density.	(37)
Optimum N level vs higher or lower N for fibre fractions	Optimum N produced the lowest NDF (62.9 %), ADF (42.1 %), hemicellulose, ADL, improving digestibility; both lower N and excess N increased fibre fractions.	(37)
150 % RDF vs 0 % RDF	150 % RDF increased CP content by 20.2 %, EE by 20.1 % and ash by 23.3 % over control, while also reducing NDF by 3.49 %, ADF by 3.54 % and ADL by 7.65 %, thus improving forage quality.	(25)
100 % RDF vs organic manures alone (FYM, sheep manure)	100 % RDF produced higher green fodder yield and improved crude protein and overall fodder quality compared with only organic manures, showing the role of mineral nutrients in protein synthesis.	(38)
RDF + $ZnSO_4$ atat 10 kg/ha soil + 0.3 % foliar spray vs RDF alone	Higher soil Zn (10 kg/ha) plus foliar Zn at 0.3 % at 45 DAS produced the highest CP and crude fibre yields and nutrient uptake (N, P, K, Zn), enriching overall nutritional quality of fodder maize.	(36)
100 % RDF + foliar 1 % $ZnSO_4$ (20, 45, 60 DAS) vs 100 % RDF alone	100 % RDF with foliar 1 % $ZnSO_4$ at 20, 45 and 60 DAS recorded significantly higher CP, total ash and ether extract and lower crude fibre and NDF than RDF alone, indicating improved protein density and digestibility.	(39)
Integrated organic nutrient management (e.g., FYM + vermicompost + biofertilisers) vs farmer practice	Integrated organic treatments increased CP, reduced NDF and ADF and improved relative feed value in fodder maize within cereal–legume systems, showing that organics can enhance nutritional quality while sustaining yield.	(40)

CP: crude protein; EE: ether extract; ADF: acid detergent fibre; ADL: acid detergent lignin; NDF: neutral detergent fibre; RDF: recommended dose of fertiliser; DAS: days after sowing; N: nitrogen; Zn: zinc; $ZnSO_4$: zinc sulphate.

Pre-harvest management of maize fodder

The rigid composition of lignocellulosic biomass poses challenges for microorganisms and animals in breaking it down and accessing the nutrients found in fodder maize. Various pre-treatment techniques have been developed to disrupt the lignocellulosic matrix and improve biomass digestibility. These include physical, chemical and biological pre-treatments, which are illustrated in Fig. 1. Suitable pre-treatment methods are necessary due to the complex lignocellulosic structure, composed of cellulose, hemicellulose and lignin, which hinders the extraction of fermentable sugars and other valuable compounds from biomass (41, 42). These techniques increase biomass surface area and porosity for enzymatic hydrolysis by solubilising lignin, modifying its structure or disrupting the crystalline arrangement of cellulose (41). Similar to this, physicochemical techniques like steam explosion using heat and pressure efficiently break down the lignocellulosic matrix, whereas physical pre-treatments like milling and grinding enhance the surface area of biomass (43).

Biological pretreatments, which utilise microbial or enzymatic processes, provide an eco-friendly option by selectively degrading lignin under mild conditions but generally require longer processing times (3). Biomass pretreatment partially degrades the lignocellulosic matrix, making cellulosic substrates more accessible for subsequent processing, such as enzymatic hydrolysis, in which cellulases and hemicellulases convert them into fermentable sugars (44).

Selecting one pre-treatment technique that can be applied universally is challenging due to the diverse chemical compositions and structural properties present in various biomass feedstocks (41). Among the physical pretreatment techniques, mechanical methods such as milling reduce particle size and disrupt cellulose crystallinity, improving biomass accessibility. These methods provide manageable particle size and lower water consumption but require high energy input and offer limited lignin removal (45).

Optimising pre-treatment methods is crucial for increasing the efficiency of enzymatic hydrolysis, which might increase cellulose conversion rates from 20–98 % (46). The use of laccase and versatile peroxidase for enzymatic pre-treatment can improve the degradation of lignin (47). Alkaline pre-treatment using 0.5% sodium hydroxide (NaOH) for 2 hr significantly increased the solubilisation of maize residues by up to 59 %, reaching solubilisation levels of as high as 80 %, while retaining a larger quantity of cellulose in the solid residue (48). Advanced pre-treatment techniques such as ionic liquids, supercritical carbon dioxide (CO_2), low-temperature steep delignification and co-solvent enhanced lignocellulosic degradation are more effective than traditional acid or alkali methods and also reduce the production of harmful byproducts (49). Treatment with lignocellulolytic enzymes produced by the white-rot fungus *Pleurotus ostreatus* reduced lignin content, enhanced antioxidant capacity and improved *in vitro* fermentation characteristics of maize silage (50).

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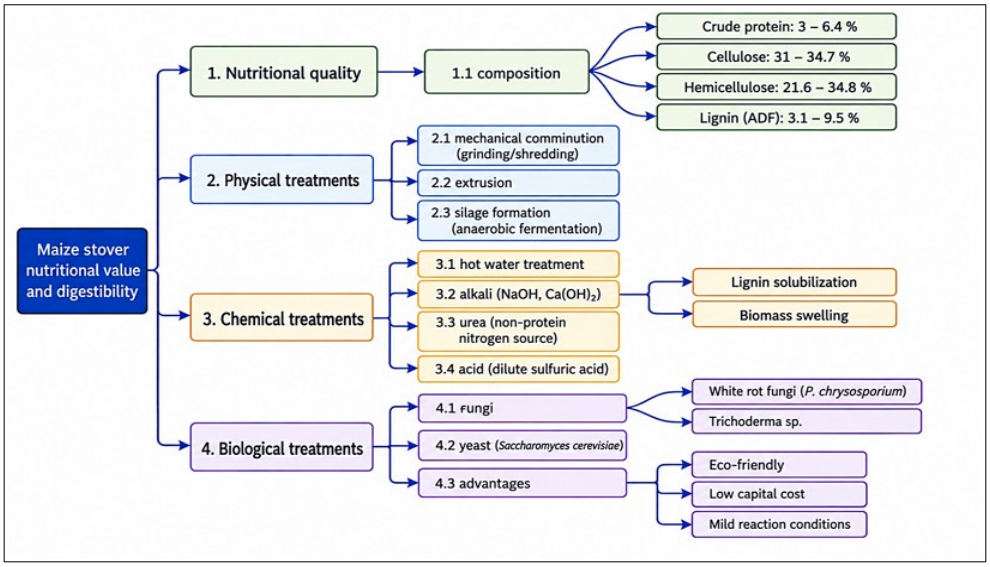


Fig. 1. Various strategies utilised for the delignification of crop residues (3).

ADF: acid detergent fibre.

Post-harvest management of maize fodder

Advanced post-harvest methods, like controlled environment storage and hermetic sealing, are essential for minimising the significant losses commonly associated with conventional storage methods (51). Unlike conventional storage, where there is high susceptibility to pests and fungi, along with high levels of moisture variations, hermetic systems form an atmosphere characterised by limited amounts of oxygen and high amounts of CO_2 that hinder breathing by insects and growth of fungi (52–54). These advantages not only preserve the nutritional quality and physical integrity of fodder maize but also enhance its market value and suitability for both livestock feed and human consumption.

Developing nations face challenges in adopting advanced storage technologies like hermetic bags due to costs, lack of awareness, ignorance and restricted access to these advances (55, 56). The efficacy of hermetic storage has been widely demonstrated, with several studies reporting reductions in post-harvest losses exceeding 85 %, indicating its considerable potential to improve food security and farm profitability in developing countries (57). Storage performance, in contrast, varies with the initial level of insect infestation, storage duration and the structural integrity of the storage material (58). Super grain bags effectively maintain hermetic conditions under normal storage but remain susceptible to perforation by larger grain borers such as *Prostephanus truncatus*, reducing their protective capacity (58). Studies reporting successful suppression of *P. truncatus* and *Sitophilus oryzae* populations in hermetic bags indicate that effective pest control depends on preserving an airtight environment and minimising pre-storage infestations (58). These contrasting observations demonstrate that the effectiveness of hermetic storage depends not only on the storage technology itself but also on storage management practices, pest pressure and the durability of the storage material.

Advanced hermetic technologies, including GrainPro Cocoons and purdue improved crop storage (PICS) bags, further illustrate the benefits of modified-atmosphere storage by creating conditions that disrupt insect metabolism without relying on chemical insecticides (59). Widespread adoption in many developing countries remains limited because of high initial costs, inadequate farmer awareness and restricted access to these technologies (55, 56). In addition to increasing food availability, this decrease in losses reduces the health hazards related to mycotoxin contamination, a common problem in traditionally kept maize (53, 58, 59). Improvements in material durability, reductions in production costs and strengthened farmer extension programmes are therefore essential for maximising the benefits of hermetic storage. Future research should focus on evaluating the long-term durability, economic feasibility and performance of different hermetic systems under diverse agro-climatic conditions to identify storage solutions that are both technically effective and economically accessible for smallholder farmers.

In vitro and *in vivo* digestibility assessment techniques

The actual nutritional evaluation of maize requires both *in vitro* and *in vivo* evaluation methods, as data from either method independently fails to fully predict *in vivo* digestive performance. *In vitro* experiments give fast results of the quality of the feed, but the *in vivo* techniques allow for the observation of the complex processes that take place in the digestive system. These opposing findings suggest that the influence of moisture is not only determined by the harvesting process but also by the subsequent processing, underscoring the importance of viewing the digestibility results from the perspective of the entire system of production.

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In digestibility, both biochemical and agronomic treatments play a role. Fibrolytic enzymes such as cellulase, xylanase and pectinase greatly increased the *in vitro* digestibility of dry matter, organic matter and fibre of maize residue, especially the combination containing cellulase enzymes (60, 61). These observations have been made mainly in laboratory tests and they will need to be validated further by experiments with animals to determine whether these hold in practical feeding situations. Harvesting timing is also an important factor, as the fodder harvested at 40 days showed higher crude protein content and better dry matter digestibility than the fodder harvested at 60 days (62). This suggests that physiological maturity may exert a greater influence on feed quality than post-harvest interventions alone.

The nutritional variation of plant parts and maize varieties makes feed evaluation even more difficult. Animal studies also identified hybrid-specific differences in fibre digestibility that were not detected by conventional feed tables or near-infrared (NIR) spectroscopy (63), demonstrating the limitations of relying solely on laboratory predictions. The lower methane production observed in the DHM 117 variety without compromising digestibility suggests that varietal selection could improve both feed efficiency and environmental sustainability (64). Overall, the nutritive quality of fodder maize is controlled by the interaction of genotype, harvest time, process and supplementation; thus, it is indispensable to combine the *in vitro* and *in vivo* techniques to evaluate its nutritional quality for animal feeding.

Advances in silage technology

The primary objective of ensiling is to preserve surplus fodder and its nutritional value, which is achieved by maintaining an anaerobic environment and adequate acidity (65). The principle of the silage creation is to promote an increased proliferation of the lactic acid bacteria by compaction and sealing to create anaerobic conditions (66). These bacteria convert fermentable sugars into lactic acid, acetic acid and other organic acids, reducing the pH to approximately 3.8–4.2 and suppressing the growth of spoilage microorganisms such as *Clostridia*, yeasts and moulds (67). Rapid acidification also limits plant enzymatic activity and undesirable microbial proliferation, preserving forage stability and nutritional quality (68, 69). The efficiency of this process is influenced by dry matter content, pH, ammonia concentration and aerobic stability, indicating that silage quality depends on the interaction of multiple fermentation parameters rather than pH alone (70).

Maize exhibits a high content of fermentable water-soluble carbohydrates (such as fructose, sucrose and glucose) and low buffering capacity (200–250 milliequivalents per kilogram (mEq/kg) of dry matter), further enhancing its superior qualities for silage making, including high palatability, succulence, nutritional richness and a lack of anti-nutritional factors (1, 71). The ensiling process begins with an aerobic stage, during which facultative organisms consume the remaining oxygen, followed by anaerobic fermentation by lactic acid bacteria that converts carbohydrates into lactic acid, acetic acid, alcohols and CO_2, resulting in a stable acidic environment (2, 72, 73). Maintaining these conditions throughout storage is equally important because oxygen infiltration during feed-out or poor silo management can stimulate acid-tolerant yeasts, increase pH and accelerate nutrient losses through secondary fermentation (2). This demonstrates that successful silage preservation depends not only on rapid fermentation but also on maintaining anaerobic conditions throughout storage.

Current advances in silage technology are increasingly focused on improving fermentation efficiency and nutrient preservation through targeted additives. Functional classifications of silage additives (Tables 3 and 4) demonstrate that their roles extend beyond fermentation enhancement to improving microbial ecology, nutrient stability and aerobic stability. Microbial inoculants are particularly effective in promoting desirable lactic acid bacteria, accelerating fermentation, suppressing undesirable microorganisms and preserving nutrients, thereby improving the feeding value of maize silage (Fig. 2). These developments indicate that silage quality is determined by the combined effects of crop characteristics, fermentation management and additive technologies rather than by any single factor.

Conversion of maize silage into blocks for better storage and transport

Transportability is a major advantage of baled maize silage, enabling efficient fodder movement from surplus to deficit regions while reducing environmental problems associated with paddy straw burning and lowering silage production costs (78, 79). The effectiveness of this approach depends on harvesting and baling technologies that maximise bale density and minimise handling costs. Single-pass whole-plant harvesters integrate grain collection with stover baling, producing high-density bales that reduce the number of loads required for transportation and occupy less storage space, thereby lowering transportation and storage costs (79). These benefits can only be sustained when appropriate ensiling techniques, moisture management and airtight wrapping are used, essential for maintaining fermentation quality and minimising nutrient losses in baled silage (78). Integrated machines capable of crushing, shredding and baling further enhance operational efficiency, particularly in hilly regions and smallholder farming systems, by reducing labour requirements while producing denser bales (80).

Successful storage relies on airtight plastic wrapping that maintains anaerobic conditions for lactic acid fermentation, whereas silage additives improve pH stability, reduce dry matter losses and enhance aerobic stability during storage and feed-out (70, 78). Moisture content, chop length and additive selection collectively influence fermentation efficiency and the final nutritional quality of silage, indicating that mechanisation alone cannot guarantee successful preservation. These advances improve storability, transportability and year-round availability of maize silage, strengthening livestock production (81, 82).

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Table 3. Silage additives and their functional advances in enhancing fermentation quality

Additive type	Key function	Advances	Limitations
Homofermentative LAB	Rapid acidification	Promotes a rapid decline in pH, inhibiting harmful microorganisms such as *Clostridia*.	Limited aerobic stability during feed-out.
Heterofermentative LAB	Aerobic stability	Strains like *Lentilactobacillus buchneri* convert lactic acid into acetic acid, which acts as a potent antifungal agent during the feed-out phase.	Performance depends on storage time and ensiling conditions.
Dual-strain inoculants	Synergistic effect	Combinations of *Lactococcus lactis* and *L. buchneri* provide both rapid initial acidification and long-term stability.	Require proper inoculation and fermentation conditions.
Bacteriocins and chemicals	Spoilage inhibition	Natamycin and other antimicrobial compounds suppress yeast and mold growth, while chemical preservatives such as propionate salts, sodium benzoate and potassium sorbate improve aerobic stability. Their combination with LAB provides complementary protection during fermentation and feed-out.	Effectiveness depends on dose, silage composition and oxygen exposure; best results are obtained when combined with LAB and proper ensiling practices.

LAB: *Lentilactobacillus buchneri.*

Table 4. Functional classification of silage additives: Key mechanisms and recent innovations

Crop/Hybrid	Additive/Inoculant	Maturity stage/Initial DM	Ensiling duration (days)	pH	Lactic acid (g kg^{-1} DM)*	Acetic acid (g kg^{-1} DM)*	Aerobic stability (h)	DM loss (%)	Crude protein (%)	References
Maize stover	Natamycin (8 g t^{-1}) + *Lentilactobacillus buchneri* (1×10^5 cfu g^{-1} FM)	Two-thirds milk line / 62.38 % DM	60	3.74	NR	NR	>240	NR	7.10	(76)
Maize stover + banana pseudostem	Banana pseudostem (20 %)	Two-thirds milk line / 59.48 % DM	60	3.77	NR	NR	NR	NR	7.13	(76)
Maize stover	*Limosilactobacillus fermentum* (2×10^6 CFU g^{-1} FM)	35.16 % DM	50	3.80	9.28	2.03	264.00	1.93	9.20	(2)
Flint maize	*Lentilactobacillus buchneri* CNCM I-4323 (1×10^5 CFU g^{-1})	300–350 g DM kg^{-1} FM	120	3.17	NR	-	123.00	NR	NR	(73)
Whole-plant maize (KWS STEFANO, FAO 200/220)	*L. buchneri* DSM22501 + *Lactococcus lactis* DSM11037	Late dough / 36.69% DM	60	3.80	60.54	20.63	394.80	4.00	9.38	(76)
Whole-plant maize (Hybrid 32R22H)	Yellow serofluid + *Lentilactobacillus buchneri*	34.99 % DM	90	4.20	7.49	8.77	NR	NR	8.48	(77)
Whole-plant maize (Hybrid 32R22H)	Yellow serofluid only	34.99 % DM	90	4.23–4.25	5.18	8.94	NR	NR	7.92	(1, 77)
Whole-plant maize (KWS SANDIAS, FAO 180)	*Lentilactobacillus buchneri* DSM22501 + *Lactococcus lactis* DSM11037	Late dough / 34.39 % DM	32	3.83	47.30	14.20	146.4	2.66	5.41	(1)

DM: dry matter; DSM: Deutsche Sammlung von Mikroorganismen (German collection of microorganisms); NR: not reported.

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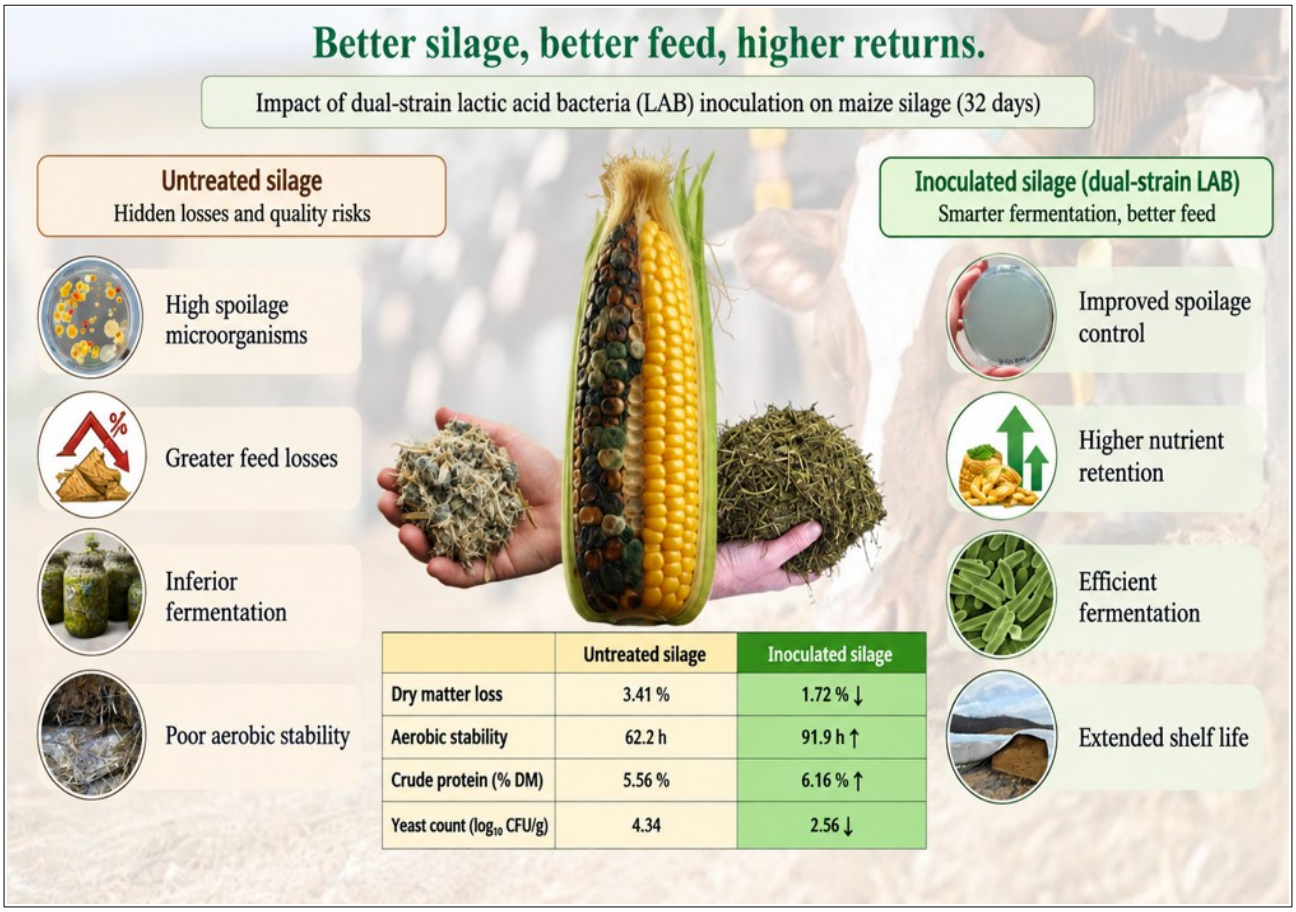


Fig. 2. Microbial inoculants for superior maize silage quality (1, 2).
DM: dry matter; CFU: colony forming unit; LAB- *Lentilactobacillus buchneri.*

Fibre fractions and anti-nutritional factors

The presence of antinutritional compounds such as tannins, phytates and saponins limits the nutritional value of maize fodder by reducing nutrient availability and impairing digestive efficiency in livestock (83). Their impact depends on both concentration and composition, making cultivar selection and harvest management important determinants of feed quality and the economic efficiency of livestock production through improved feed conversion and animal performance (10). Reducing these compounds without compromising essential nutrients remains a major challenge, driving research into genetic improvement, post-harvest processing and biochemical interventions (84). Fermentation with *Bacillus subtilis* has shown potential to degrade phytic acid and water-unextractable arabinoxylans in maize gluten feed (85), while biofortification has been proposed as a complementary strategy to improve nutrient availability and animal health (86). These approaches indicate that enhancing feed quality requires both reducing antinutritional compounds and improving nutrient accessibility.

The mechanisms through which antinutritional factors impair feed utilisation differ but collectively reduce nutrient assimilation. Phytic acid chelates essential minerals such as iron (Fe) and Zn while inhibiting digestive enzymes including tyrosinase, trypsin, pepsin, lipase and amylase, thereby decreasing mineral bioavailability and overall digestion (87). Tannins form stable complexes with proteins and amino acids, lowering protein digestibility and potentially causing gastrointestinal lesions (88). Saponins can alter intestinal permeability and exhibit hemolytic activity, further reducing nutrient absorption and animal performance (84). Although some of these compounds may exert beneficial biological effects at low concentrations, their overall influence in fodder systems is predominantly detrimental when present in higher amounts (83). Fermentation and enzymatic hydrolysis improve digestibility by degrading antinutritional compounds, breaking down complex carbohydrates and releasing fermentable sugars that increase energy availability for ruminants (89). These findings suggest that integrated strategies combining crop improvement with biological processing are likely to be more effective than relying on a single intervention to enhance the nutritional quality of maize fodder.

Hydroponic maize fodder and animal performance

Hydroponic maize fodder (HMF) has emerged as an alternative forage production system for improving feed availability under conditions of limited land and water resources. Fodder maize is a high-yield, energy-dense

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forage that supports livestock growth, lactational performance and overall health because of its high digestibility and superior nutrient content compared with many other non-leguminous fodders (82). The nutritional benefits are influenced by the production system and feeding strategy rather than maize alone. Studies involving HMF showed that replacing conventional fodder maintained nutrient intake and milk yield while improving the utilisation of dry matter, crude protein and total digestible nutrients, with increases in 4 % fat-corrected milk and milk fat content (90). Cows fed HMF exhibited superior fibre degradation (59.21 % vs. 53.25 %) and higher crude protein digestibility (72.46 % vs. 68.86 %), which were associated with a 13.7 % increase in milk yield and improved feed efficiency (91), indicating that enhanced nutrient utilisation is a key contributor to improved productivity.

The positive effects of HMF extend beyond dairy cattle. Calves receiving a 20–40 % HMF diet exhibited accelerated daily weight gain, improved feed conversion ratio, greater nutrient digestibility and increased N retention without adverse effects on haematological parameters (92). In Red Sokoto bucks, supplementation with 750 g HMF maintained rumen pH within the optimal range, stimulated volatile fatty acid production and microbial activity and improved nutrient utilisation and growth performance (93). Whole-plant maize silage also modified rumen microbial populations in beef cattle, promoting metabolic pathways associated with carbohydrate, amino acid and nucleotide metabolism while maintaining a favourable rumen environment for efficient fermentation and growth (94). These findings indicate that the benefits of maize-based feeding are closely linked to improvements in rumen function and microbial activity.

Silage inoculants also influence feed quality through different mechanisms. *Lentilactobacillus buchneri* improved silage fermentation by reducing pH and ammonia-N and increasing lactic acid concentration and digestibility, although it increased dry matter loss. The heterofermentative bacterium *L. buchneri* improves aerobic stability through the production of acetic acid and 1, 2-propanediol, although this may increase fermentative dry matter losses (95). These contrasting responses highlight that no single management practice optimises all aspects of fodder quality. Hydroponic maize fodder offers an additional advantage by requiring minimal land and enabling production in backyards, on rooftops, or in indoor systems, making it a promising option for meeting future fodder demands amid increasing land and resource constraints.

Economic implications of maize fodder quality improvement technologies

Economic viability is a critical component of maize fodder quality improvement technologies, as their adoption depends on the balance between additional input costs and the financial benefits derived from enhanced forage quality, livestock productivity and farm profitability. Quality improvement technologies, including improved silage hybrids, balanced fertilisation, cereal–legume intercropping, micronutrient application and silage additives, involve additional production costs that are compensated by higher fodder productivity, improved feed utilisation and enhanced livestock performance (82). The magnitude of economic benefit varies across technologies, indicating that the strongest biological response does not always yield the greatest financial return.

Cost-benefit analyses consistently show that integrated production systems are more profitable than single-input interventions. Maize–cowpea intercropping (2 : 1) produced the highest green fodder yield together with the highest net income (₹38747 ha^{-1}) and benefit-cost ratio (1.78), exceeding sole maize because the additional legume biomass improved fodder quality while reducing dependence on purchased protein supplements (96). Grain maize intercropped with fodder maize and fodder cowpea under 125 % recommended fertiliser dose generated greater net returns and benefit-cost ratio than sole cropping or the highest fertiliser level (150 % RDF), indicating that moderate nutrient intensification provides better economic efficiency than maximising fertiliser inputs (97). Balanced application of 90 kg N ha^{-1} and 60 kg P_2O_5 ha^{-1} significantly increased fodder yield, nutrient uptake, quality and profitability, demonstrating that optimum nutrient management provides greater economic returns than inadequate fertiliser application (98).

Return on investment (ROI) provides additional evidence for the financial benefits of improved maize production technologies. Farmers adopting improved maize production technologies achieved higher net profits (₦438367 ha^{-1}) than non-adopters (₦374426 ha^{-1}) and the return on investment increased from 6.00–7.64 for every unit invested (99). The combined adoption of complementary maize production technologies reduced production costs by 26.4 %, increased both producer and consumer surplus and generated greater economic benefits than the adoption of individual technologies alone (100).

Improved maize fodder systems also enhance livestock productivity and overall farm profitability. Better-quality fodder increases digestibility and nutrient utilisation, reduces the requirement for purchased concentrate feed and improves milk yield, growth rate and feed conversion efficiency (82). Feed accounts for approximately 65–70 % of total livestock production costs, making improvements in fodder quality an effective approach for increasing dairy farm profitability (96). Specialised silage hybrids, microbial inoculants and intensive nutrient management require greater initial investment, making adoption more feasible when supported through extension services, input subsidies and improved access to agricultural credit. Future studies should integrate biological responses with whole-farm economic analyses, including investment costs, feed savings, livestock productivity and long-term profitability, to identify technologies that are both agronomically effective and economically sustainable.

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4. Conclusion

Improving maize fodder quality requires an integrated combination of improved germplasm, balanced nutrient management, appropriate harvest timing and efficient preservation technologies. Genetic and agronomic interventions can enhance protein content, reduce fibre fractions and improve digestibility, while silage inoculants and biomass pretreatments help minimise nutrient losses and improve feed stability. Integrating these approaches can increase feed efficiency, livestock productivity and economic returns while contributing to sustainable fodder security under resource constraints.

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Authors' contributions

AA and RK designed the concept and methodology. RK, KT, PJ and VBRP contributed to the writing and preparation of the original draft. AA, RK, KT, PJ, VBRP and MU contributed to the review and editing of the manuscript. KT, RK, AA, PJ, VBRP and MU supervised the study. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

Declaration of generative AI and AI-assisted technologies in the writing process

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