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Research article

# Comparative analysis of nutritional attributes of maize fodder and silage: plant breeding implications

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## Abstract

Present study evaluated the nutritive value of whole-fodder maize silage (WCMS) and fodder from 18 maize hybrids, comparing before (fresh fodder) and after ensiling. The nutrient composition was analyzed, focusing on crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), ash content, cell wall components (lignin, cellulose, hemicellulose), in vitro dry-matter digestibility (IVDMD), in vitro NDF digestibility (IVNDFD), organic matter digestibility (OMD), and metabolizable energy (ME). Results showed a significant increase in IVDMD (11.13%), OMD (6.83%), and IVNDFD (8.66%) post-ensiling, while CP content remained constant (0.15% increase) with a minor DM loss (2.13%). Among the hybrids, JQPM5 exhibited the highest IVDMD (72%), followed by JH20209, JQPM2 and JQPM2 (69.87%). Additionally, significant genetic variability was observed in ADF, EE, and ADL, indicating the potential for selective breeding to improve silage quality. Overall ensiling enhanced the digestibility and energy profile of maize fodder, and the observed genotypic variability highlights the potential for genetic improvement of silage quality through targeted breeding.

**Keywords:** Digestibility parameters, Fermentation process, Hybrid evaluation, Maize silage, Nutritional quality, Ruminant nutrition.

## Introduction

Maize (*Zea mays* L.) is one of the most widely cultivated and consumed cereal crops worldwide. It is primarily grown for grain and industrial applications and serves as a vital source of food and feed (Pereira *et al*., 2020; Sharma *et al*., 2024). Owing to its remarkable adaptability across diverse agro-climatic conditions, maize has proven superior in green fodder quality and silage production. It provides animals with highly palatable, succulent, and nutritionally dense feed that is free from antinutritional factors (Kumar *et al*., 2023). Maize is also the most preferred crop for silage production because its fodder is rich in easily fermentable water-soluble carbohydrates such as fructose, fructans, sucrose, and glucose, and exhibits a low buffering capacity (200-250 mEq $kg^{-1}$ dry matter) (Ballard *et al*., 2001). In India, it is recognised as an excellent fodder crop due to its fast growth, high biomass, wide adaptability, lack of anti-nutritional compounds, and high palatability and digestibility (Arya *et al*., 2015; Brar *et al*., 2024).

Seasonal fluctuations in forage availability often constrain livestock productivity. Consequently, silage making has emerged as a reliable method for conserving forage and minimising post-harvest nutrient losses (Fulgueira *et al*., 2007). Ensiling allows moist forage to be preserved until use, ensuring a continuous supply of digestible nutrients to high-producing livestock. Silage serves as a conserved nutrient source supporting rumen function and as a supplementary feed during winter or drought when pasture is inadequate. Preservation success depends on maintaining anaerobic conditions, low pH, and optimal production of lactic and acetic acids by lactic acid bacteria (Daniel *et al*., 2013).

India continues to face a 50-60 % deficit in quality fodder, resulting in lower milk productivity (Saxena *et al*., 2020). Adoption of large-scale silage technology can substantially bridge this gap. The global maize-silage market is projected to grow at a compound annual growth rate (CAGR) of 7.84 % between 2021 and 2030 (Karnatam *et al*., 2023), driven by the rising demand for sustainable feed resources. With the dairy sector expanding by 4-5 % annually, the demand for silage maize is set to rise further. Mechanisation, reduced labour needs, timely land availability for subsequent crops, and easy storage options have made silage maize an economically attractive enterprise. India's silage market, estimated at 4-5 million tonnes, has significant potential to enhance farmer income and increase cropping intensity, particularly with short-duration silage maize (~80 days) (Rakshit *et al*., 2023).

Despite this growing importance, a knowledge gap exists regarding the comparative performance of commercially grown and advanced maize hybrids for silage quality. While earlier studies have demonstrated that silage quality is influenced by cultivar genetics and crop management (Widdicombe and Thelen, 2002; Bamboriya *et al*., 2020), there is still limited information on how variations in the chemical composition of fresh fodder translate into differences in silage fermentation characteristics and nutritive value. Moreover, few studies have linked the initial forage composition with the biochemical end-products of fermentation (Huhtanen *et al*., 2007; Kung *et al*., 2018; Mogodiniyai, 2016). In this context, the present study was undertaken to (i) evaluate a set of maize hybrids for their chemical composition and silage quality parameters; (ii) determine the relationships between fresh fodder characteristics and silage quality traits; and (iii) identify promising hybrids suitable for high-quality silage production. In summary, the study addresses the lack of systematic evaluation of maize hybrids for both fresh fodder and silage characteristics under north-western Indian conditions, aiming to generate information that can guide hybrid selection and breeding strategies for enhanced silage quality and livestock productivity

## Materials and Methods

***Site and experimental design:*** The field experiment was conducted during *Kharif* 2022 at the Maize Experimental Field, Punjab Agricultural University (PAU), Ludhiana, India. Eighteen advanced maize hybrids were evaluated in a randomized block design (RCBD) with two replications. Each hybrid was planted in two rows of 4.0 m length, spaced 60 cm apart, with 20 cm plant-to-plant spacing. Border rows were planted to minimize edge effects. Standard agronomic and plant protection practices recommended by PAU were followed to raise a healthy crop. Of the 18 hybrids tested, five were released hybrids and 13 were advanced entries (five QPM and eight non-QPM). For sampling, plants of each hybrid were harvested 10 cm above the ground at the half milk line stage. At this stage, approximately half of the kernel contains milky endosperm, which supports efficient fermentation, while the remaining content comprises hard starch that improves digestibility for ruminants (Ma and Dwyer, 2012). The harvested plants were chopped using a chaff cutter. Half of the chopped material was used for proximate analysis of fresh fodder, and the remaining half was packed into 2 kg silage bags. The bags were tightly sealed to create anaerobic conditions and stored at room temperature for 45 days.

Ensiling was based on anaerobic fermentation, in which epiphytic lactic acid bacteria (LAB) convert water-soluble carbohydrates (WSC) into organic acids, mainly lactic acid. After 45 days, the silage bags were weighed to determine dry matter (DM) loss. Approximately 400 g of homogenized silage from each sample was oven-dried at 55-60 °C for 72 hours. The pH of the silage was determined using a digital pH meter, following the method described by Da Silva *et al* (2016).

***Observations and chemical analysis:*** Standard biochemical procedures were followed to estimate silage quality parameters- DM, DM loss, ash content, crude protein (CP), ether extract (EE), acid detergent fibre (ADF), neutral detergent fibre (NDF), and acid detergent lignin (ADL). DM losses were calculated as the difference between the mass recorded at the time of filling and at the time of opening the silo, adjusted for DM content, and expressed as a percentage of the initial mass. Ash, EE, and CP were estimated according to AOAC (1995), while NDF, ADF, and ADL were determined as per Van Soest *et al*. (1991). The ADF method does not directly measure digestibility; a higher ADF concentration generally indicates lower digestibility. Total digestible nutrients (TDN) were calculated using the equation (NRC, 2001):

$$\text{TDN (\%)} = 87.84 - (\text{ADF\%} \times 0.70)$$

Cellulose content was derived by subtracting ADF from NDF, and hemicellulose by subtracting ADL from ADF. All chemical analyses were carried out on oven-dried, ground silage samples at the Animal Nutrition Laboratory, Guru Angad Dev Veterinary and Animal Sciences University (GADVASU), Ludhiana. In vitro dry matter digestibility (IVDMD) and in vitro NDF digestibility (IVNDFD) were determined following Menke *et al.* (1979) and Blümmel *et al.* (1997) using the in vitro gas production method. The method also provided estimates of organic matter digestibility (OMD) and metabolizable energy (ME).The Institutional Animal Care and Use Committee of GADVASU approved all procedures involving animals. Rumen inoculum was prepared by collecting rumen fluid and solids from a rumen-cannulated buffalo, which were mixed to form a composite inoculum. For 24-hour incubation, 0.375 g of ground sample was placed into glass syringes (32 mm internal diameter, 150 mL capacity) fitted with lubricated pistons. Each syringe was connected to a 4-5 cm silicone tube closed with a plastic clip to maintain airtight conditions.

**Statistical analysis:** All biochemical and proximate analyses were performed in triplicate. Analysis of variance (ANOVA) at $P$<0.05 was conducted separately for all test traits using R software version 4.2.3 (R Core Team, 2023). Descriptive statistics, including means and standard deviations, were calculated, and the mean of each replicate was used for further analysis. Differences between fresh forage and silage were evaluated using a $t$-test. When the null hypothesis of no difference was rejected, it indicated a significant variation in the chemical composition of the silage compared to the corresponding forage. Correlation analysis was performed using the *ggplot2* package in R (version 4.2.3). Phenotypic coefficient of variation (PCV), genotypic coefficient of variation (GCV), broad-sense heritability, and genetic advance were estimated using the *variability* package in R.

## Results and Discussion

***Quality parameters of silage:*** The quality of silage was assessed based on its fermentation characteristics, nutritive value, and feed value. The fermentation characteristics of the test hybrids (Table 1) showed significant genotypic differences in the pH of maize silage. A lower pH in silage indicates a higher lactic acid concentration, as lactic acid- being stronger than other acids present in silage such as acetic, propionic and butyric acids- is primarily responsible for pH reduction (Kung and Shaver, 2001). In this study, silage from the maize hybrid PMH 13 recorded the lowest pH (3.32), which was comparable to that of hybrid JH18064 (3.38). The pH values across different silages ranged from 3.32 to 4.53, which falls within the normal range suggested by McDonald *et al*. (1991). However, silages prepared from hybrids JQPM5 and PMH3 exhibited pH values slightly higher than the optimal range.

Lactic acid plays a crucial role in lowering the pH of ensiled forage, making it a key factor in effective fermentation (Kung and Shaver, 2001). High levels of soluble protein in silage can lead to excessive degradation, resulting in ammonia production. Ammonia ($NH_3$) combines with hydrogen ions ($H^+$) to form ammonium ($NH_4^+$), thereby preventing the silage from attaining the desired low pH (Kung *et al*., 2018). In this study, ammonia production (as a percentage of total nitrogen) was significantly lower in the silages from hybrids JH19019 and PMH5, both recording 0.22%. The range of ammonia production (0.22%-0.29%) indicated excellent silage quality, as per Wilkinson (1999). The TSS content in maize stalks is associated with improved aroma and acidity in silage. Elevated sugar content enhances fermentation efficiency, producing superior silage quality. Simple sugars are more readily converted into lactic acid and ethanol than complex carbohydrates, thereby promoting efficient fermentation (Bian *et al*., 2015). Similar findings were reported by Chaudhary *et al*. (2016), who observed that silage samples with pH below 4.0 demonstrated excellent preservation. Jalč *et al*. (2010) reported pH values ranging from 3.52-3.80 in 2009 and 3.58-4.14 in 2010 in grass and corn silages, aligning with the range observed in this study. Kung et al. (2018) recorded pH values between 3.7 and 4.2 for low-moisture maize silage and 4.0-4.5 for high-moisture maize silage. Brar et al. (2021) also reported similar values (3.6-4.3) in maize silage.

The DM content of silages from the tested hybrids varied from 27.50% to 35.50% (Table 2). Silages from hybrids JQPM4 (35.3%) and JQPM1 (35.0%) recorded significantly (P<0.05) higher DM content, while the lowest DM was observed in PMH5 (27.5%). DM is a critical determinant of harvest maturity in silage maize and is an independent trait not solely governed by flowering time or grain maturity. This highlights the potential for selecting early-maturing hybrids without compromising yield. Previous studies have indicated that DM content is influenced by genetic factors that enhance plant growth and biomass accumulation (Karnatam *et al*., 2023). These mechanisms involve genes linked with photosynthetic efficiency, cell wall architecture, and plant growth-promoting regulators (PGPRs), with genotypes exhibiting higher photosynthetic efficiency tending to accumulate more biomass (Peña *et al*., 2023).

Proximate analysis revealed that CP content in silages of different hybrids ranged from 8.10% (JQPM3) to 10.62% (PMH13). Protein is a critical component of livestock nutrition, and since protein in silage cannot be directly measured, CP- representing total nitrogen- is used to estimate true protein and non-protein nitrogen. Maize silage typically has low protein content (Khan *et al*., 2015). Adequate CP levels are essential for efficient fermentation, as bacteria require sufficient nitrogen for metabolic processes. Inadequate CP can adversely affect silage intake and digestibility. Although CP is a useful indicator of feed quality, it does not fully represent the energy value of silage; hence, low CP content can be compensated by supplementing rations with oilseed meals and leguminous feeds.

Ash content in the silages varied from 3.5 to 7.52%, with the silage of the JH22148 hybrid showing the highest ash (7.25%) content, followed by JH19011 (7.15%) and JH20209 (6.92%). Ash content in silage represents the inorganic non-combustible material, primarily reflecting the total mineral content (including calcium, phosphorus, potassium, and magnesium). Maize silage typically has an ash content ranging from 5.0 to 9.0% of the DM. Although ash does not contribute to the caloric value, it provides essential nutrients like magnesium, calcium, and potassium to ruminants. Feeding dairy cows with

**Table 1.** Nutrient quality parameters of ensiled hybrids

| S. No | Hybrids | DM (%) | CP (%) | Ash (%) | ADF (%) | NDF (%) | ADL (%) | EE (%) | Cellulose (%) | Hemi-cellulose (%) | TDF (%) | OMD (%) | IVNDFD (%) | IVDMD (%) | ME (%) | SCFA (%) | Amm-onia (%) | pH | DM loss (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | JH17026 | 33.00 | 9.40 | 4.75 | 27.45 | 61.35 | 3.60 | 2.45 | 23.85 | 33.90 | 68.63 | 69.65 | 53.53 | 69.87 | 7.60 | 0.73 | 0.24 | 3.90 | 2.21 |
| 2 | JH18064 | 28.75 | 9.77 | 4.55 | 31.65 | 57.10 | 4.27 | 2.16 | 27.39 | 25.45 | 65.69 | 69.12 | 48.67 | 69.33 | 7.89 | 0.74 | 0.26 | 3.38 | 3.11 |
| 3 | JH19011 | 33.00 | 8.47 | 7.15 | 36.30 | 59.32 | 6.25 | 2.55 | 30.05 | 23.02 | 62.43 | 66.45 | 47.34 | 66.93 | 8.22 | 0.74 | 0.28 | 4.40 | 2.74 |
| 4 | JH19019 | 30.75 | 9.17 | 5.50 | 26.90 | 62.00 | 2.55 | 2.43 | 24.35 | 35.10 | 69.01 | 65.96 | 48.39 | 66.40 | 6.56 | 0.61 | 0.22 | 3.52 | 3.35 |
| 5 | JH20209 | 34.75 | 10.27 | 6.92 | 24.45 | 60.60 | 2.60 | 2.67 | 21.85 | 36.15 | 70.73 | 69.61 | 53.96 | 69.87 | 7.36 | 0.72 | 0.26 | 4.27 | 3.14 |
| 6 | JH22147 | 33.50 | 8.64 | 6.30 | 41.95 | 68.60 | 4.60 | 2.80 | 37.35 | 26.65 | 58.48 | 69.32 | 58.38 | 69.60 | 7.67 | 0.70 | 0.25 | 4.30 | 1.94 |
| 7 | JH22148 | 28.70 | 10.19 | 7.25 | 31.45 | 59.60 | 4.50 | 1.95 | 26.95 | 28.15 | 65.83 | 68.79 | 50.82 | 69.07 | 8.21 | 0.78 | 0.27 | 3.64 | 3.47 |
| 8 | JH22149 | 29.00 | 9.34 | 5.04 | 26.45 | 61.10 | 3.75 | 2.73 | 22.70 | 34.65 | 69.33 | 62.34 | 40.69 | 62.67 | 7.27 | 0.67 | 0.28 | 3.60 | 2.73 |
| 9 | JQPM1 | 35.00 | 9.09 | 4.75 | 37.80 | 65.20 | 2.77 | 3.22 | 35.03 | 27.40 | 61.38 | 69.32 | 55.59 | 69.60 | 7.55 | 0.75 | 0.24 | 4.26 | 3.42 |
| 10 | JQPM2 | 33.00 | 8.20 | 5.46 | 39.00 | 63.50 | 5.35 | 1.97 | 33.65 | 24.50 | 60.54 | 69.57 | 56.42 | 69.87 | 7.57 | 0.72 | 0.29 | 4.30 | 1.98 |
| 11 | JQPM3 | 34.50 | 8.10 | 4.50 | 40.95 | 67.50 | 3.64 | 1.66 | 37.31 | 26.55 | 59.18 | 66.67 | 54.02 | 67.20 | 7.27 | 0.74 | 0.23 | 4.50 | 2.30 |
| 12 | JQPM4 | 35.50 | 10.05 | 5.50 | 29.10 | 62.00 | 2.43 | 3.13 | 26.67 | 32.90 | 67.47 | 69.48 | 53.02 | 69.60 | 7.14 | 0.70 | 0.24 | 4.30 | 2.68 |
| 13 | JQPM5 | 31.00 | 10.30 | 3.50 | 28.60 | 59.60 | 2.05 | 1.76 | 26.55 | 31.00 | 67.82 | 71.90 | 56.08 | 72.00 | 7.25 | 0.72 | 0.24 | 4.29 | 2.04 |
| 14 | PMH1 | 34.50 | 8.58 | 4.15 | 32.00 | 63.15 | 4.85 | 2.39 | 27.15 | 31.15 | 65.44 | 69.08 | 54.08 | 69.33 | 7.83 | 0.72 | 0.24 | 4.20 | 2.57 |
| 15 | PMH13 | 28.25 | 10.62 | 5.65 | 35.05 | 64.81 | 5.35 | 1.97 | 29.70 | 29.76 | 63.31 | 68.99 | 55.93 | 69.33 | 8.50 | 0.79 | 0.27 | 3.32 | 1.93 |
| 16 | PMH5 | 27.50 | 9.61 | 6.45 | 25.69 | 54.55 | 3.55 | 2.55 | 22.14 | 28.86 | 69.86 | 67.60 | 44.96 | 68.00 | 7.70 | 0.75 | 0.22 | 4.53 | 3.20 |
| 17 | PMH6 | 29.70 | 9.54 | 6.14 | 33.30 | 56.65 | 4.70 | 2.45 | 28.60 | 23.35 | 64.53 | 63.96 | 42.08 | 64.80 | 7.50 | 0.67 | 0.26 | 4.29 | 4.02 |
| 18 | ADV9293 | 34.45 | 9.90 | 6.65 | 38.30 | 66.00 | 4.07 | 3.65 | 34.24 | 27.70 | 61.03 | 64.35 | 48.88 | 64.80 | 7.39 | 0.66 | 0.23 | 4.36 | 3.92 |

DM: Dry matter; CP: Crude protein; ADF: Acid detergent fiber; NDF: Neutral detergent fiber; ADL: Acid detergent lignin, EE: Ether extract; TDF: Total dietary fiber; OMD: Organic matter digestibility; IVNDFD: In vitro neutral detergent fiber digestibility; IVDM: In vitro dry matter digestibility; ME: Metabolizable energy; SCFA: Short-chain fatty acids, DM loss: Dry matter loss

**Table 2.** Nutrient quality parameters of hybrid fodder

| S. No. | Hybrids | DM (%) | CP (%) | Ash (%) | ADF (%) | NDF (%) | ADL (%) | EE (%) | Cellulose (%) | Hemi cellulose (%) | TDF (%) | OMD (%) | IVNDFD (%) | IVDMD (%) | ME (%) | SCFA (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | JH17026 | 34.15 | 9.36 | 4.75 | 27.70 | 61.40 | 3.60 | 2.24 | 24.10 | 33.70 | 68.45 | 55.44 | 42.89 | 56.27 | 7.33 | 0.73 |
| 2 | JH18064 | 29.60 | 9.81 | 4.36 | 31.80 | 57.15 | 4.30 | 2.10 | 27.50 | 25.35 | 65.58 | 61.13 | 43.02 | 61.87 | 7.41 | 0.75 |
| 3 | JH19011 | 33.80 | 8.26 | 7.11 | 36.70 | 59.25 | 6.30 | 2.48 | 30.40 | 22.55 | 62.15 | 66.67 | 53.05 | 66.93 | 7.38 | 0.74 |
| 4 | JH19019 | 31.30 | 9.12 | 5.50 | 26.60 | 62.00 | 2.50 | 2.09 | 24.10 | 35.40 | 69.22 | 57.56 | 43.34 | 58.67 | 7.00 | 0.68 |
| 5 | JH20209 | 34.79 | 10.22 | 6.82 | 24.52 | 61.40 | 2.60 | 2.43 | 21.92 | 36.88 | 70.68 | 58.33 | 42.99 | 58.93 | 7.44 | 0.73 |
| 6 | JH22147 | 33.60 | 8.72 | 6.38 | 41.90 | 68.55 | 4.90 | 2.05 | 37.00 | 26.65 | 58.51 | 59.58 | 51.02 | 60.27 | 7.26 | 0.72 |
| 7 | JH22148 | 29.20 | 10.18 | 7.25 | 31.45 | 59.65 | 4.50 | 1.75 | 26.95 | 28.20 | 65.83 | 66.81 | 54.65 | 67.20 | 7.57 | 0.78 |
| 8 | JH22149 | 30.01 | 9.32 | 5.05 | 26.90 | 61.60 | 3.80 | 2.45 | 23.10 | 34.70 | 69.01 | 55.74 | 38.91 | 56.80 | 7.15 | 0.69 |
| 9 | JQPM1 | 35.74 | 9.00 | 4.78 | 37.65 | 64.25 | 2.90 | 3.16 | 34.75 | 26.60 | 61.49 | 63.79 | 54.24 | 64.27 | 7.71 | 0.76 |
| 10 | JQPM2 | 34.50 | 8.14 | 5.42 | 39.55 | 64.25 | 4.10 | 1.61 | 35.45 | 24.70 | 60.16 | 64.26 | 54.09 | 64.80 | 7.14 | 0.73 |
| 11 | JQPM3 | 34.65 | 8.06 | 4.45 | 40.45 | 66.70 | 2.30 | 1.53 | 38.15 | 26.25 | 59.53 | 67.78 | 61.17 | 68.00 | 6.89 | 0.71 |
| 12 | JQPM4 | 36.95 | 9.89 | 5.48 | 29.85 | 63.00 | 2.50 | 3.05 | 27.35 | 33.15 | 66.95 | 60.41 | 45.06 | 60.80 | 7.61 | 0.74 |
| 13 | JQPM5 | 31.70 | 10.28 | 3.70 | 28.55 | 59.50 | 2.10 | 1.56 | 26.45 | 30.95 | 67.86 | 63.51 | 48.83 | 64.00 | 7.00 | 0.70 |
| 14 | PMH1 | 35.10 | 8.54 | 4.10 | 32.50 | 63.30 | 4.90 | 2.14 | 27.60 | 30.80 | 65.09 | 60.70 | 47.88 | 61.33 | 7.35 | 0.74 |
| 15 | PMH13 | 29.40 | 10.61 | 5.62 | 35.55 | 64.75 | 5.30 | 1.57 | 30.25 | 29.20 | 62.96 | 58.46 | 46.1 | 59.20 | 7.21 | 0.72 |
| 16 | PMH5 | 28.10 | 9.59 | 5.96 | 26.89 | 54.75 | 3.50 | 2.37 | 23.39 | 27.86 | 69.02 | 59.02 | 35.63 | 59.73 | 7.53 | 0.75 |
| 17 | PMH6 | 30.11 | 9.54 | 6.14 | 33.55 | 56.63 | 4.70 | 2.36 | 28.85 | 23.08 | 64.36 | 58.87 | 38.74 | 59.73 | 6.80 | 0.65 |
| 18 | ADV 9293 | 34.60 | 10.43 | 6.70 | 39.70 | 66.25 | 4.20 | 3.33 | 35.50 | 26.55 | 60.05 | 61.36 | 49.63 | 61.60 | 7.25 | 0.67 |

DM: Dry matter; CP: Crude protein; ADF: Acid detergent fiber; NDF: Neutral detergent fiber; ADL: Acid detergent lignin, EE: Ether extract; TDF: Total dietary fiber; OMD: Organic matter digestibility; IVNDFD: In vitro neutral detergent fiber digestibility; IVDM: In vitro dry matter digestibility; ME: Metabolizable energy; SCFA: Short-chain fatty acids, DM loss: Dry matter loss corn silage containing high ash content may enhance the uptake of endogenous minerals.

The ether extract (EE) content in the silages ranged from 1.66 to 3.65%, with the silage of ADV9293 having the highest EE (3.65%). EE represents the fat content in silage, which, not the primary source of energy for ruminants, still contributes significantly to the overall energy value. The fatty acid composition of maize silage varies depending on the maturity at harvest (Khan *et al*., 2012). Unsaturated fatty acids, particularly $\alpha$-linolenic, palmitic, and oleic acids, play a crucial role in determining silage quality and can influence milk quality when fed to dairy cows.

Acid detergent fiber (ADF) content, which measures the fiber components cellulose, lignin, and silica, was found to vary among the hybrids studied (P>0.05). ADF values ranged from 24.45 to 41.95%, with an average of 32.13%. A lower ADF value is preferred, as higher fiber content reduces digestibility in maize silage. Neutral detergent fiber (NDF), a measure of total fiber content, varied from 54.55 to 68.60%, with an average of 61.26%. The lowest ADF content was observed in hybrid JH20209 (24.45%), while the lowest NDF content was found in hybrid PMH5 (54.55%).

Acid detergent lignin (ADL) content, which is negatively associated with digestibility, varied from 2.05 to 6.25%, with an average of 3.94%. Lower lignin content is preferred for higher digestibility in silage. The lowest ADL content was recorded in hybrid JQPM5 (2.05%), followed by hybrids JQPM4 (2.43%), JH19019 (2.55%), and JH20209 (2.60%). These results are consistent with findings from Chaudhary *et al.* (2016), Brar *et al.* (2021), and Hundal *et al*. (2019). The quality of maize silage depends on the composition of its cell wall and sugar content in the stalk. These factors limit the overall fodder value of the fodder.

Cellulose and hemicellulose, which are digestible cell wall components for ruminants. The highest cellulose content was observed in hybrid JH22147 (37.35%), at par with JQPM3 (37.31%), followed by JQPM1 (35.03%). Hemicellulose content ranged from 23.02 to 36.15%, with an average of 29.24%. The highest hemicellulose content was recorded in hybrid JH20209 (36.15%), at par with JH19019 (35.10%), followed by JH22149 (34.65%). Total dietary fiber (TDF), calculated from ADF, ranged from 58 to 70.73%, with the highest TDF observed in hybrid JH20209 (70.73%), followed by PMH5 (69.86%). The in vitro dry matter digestibility (IVDMD) of silage from the tested hybrids range from 62.67 to 72%, with hybrid JQPM5 demonstrating the highest IVDMD value (72%), followed closely by hybrids JH22148 and JH19011. IVDMD serves as a critical indicator of the digestibility of silage dry matter, directly correlating to the efficiency with which ruminants can assimilate the feed's nutrients.

The IVNDFD was also assessed, measuring the digestibility of the fibrous cell wall components within the forage. Elevated IVNDFD values are indicative of more comprehensive digestion, which is paramount for the effective utilization of the fibrous fraction of the silage (Méchin *et al*., 2000). The IVNDFD values ranged from 40.69% in hybrid JH22149 to 50.38% in hybrid JH22147. A negative correlation exists between cell-wall digestibility and the concentrations of lignin and fiber within the cell walls, with higher levels of these components leading to reduced digestibility (Wolf *et al*., 1993; Argillier *et al*., 1997). Consequently, hybrids with lower lignin and fiber concentrations, such as JQPM3, enhanced digestibility, thereby contributing to superior nutritional outcomes for livestock.

The OMD of the silage varied from 62.34 to 71.90%, with the highest OMD observed in hybrid JQPM5, followed by JH17026 and JH20209. OMD is a pivotal metric that reflects the overall digestibility of the silage's organic constituents, providing a comprehensive measure of its nutritional value. The superior performance of hybrid JQPM5 across the IVDMD, IVNDFD, and OMD parameters underscores its potential as an optimal choice for producing high-quality silage. The observed variation in digestibility metrics among the different hybrids emphasizes the critical importance of selecting appropriate hybrids to maximize feed efficiency and enhance animal performance. The reduced concentrations of cell-wall lignin and fiber in hybrids like JQPM5 contribute significantly to their improved digestibility, thereby facilitating better feed intake and nutrient utilization by ruminants. Metabolizable energy and short-chain fatty acids range from 7.14-8.50% and 0.61%-0.79%

These findings are consistent with previous research, which has established the detrimental effects of elevated lignin and fiber concentrations on cell-wall digestibility (Wolf *et al*., 1993; Lundvall *et al*., 1994). Therefore, the selection of hybrids with favourable digestibility characteristics is essential for enhancing the nutritional quality of silage and optimizing livestock productivity.

***Effects of ensiling on maize nutritional characteristics*:** Significant variability in chemical and nutritional characteristics was observed among the experimental hybrids in both fresh and ensiled whole maize. This variability underscores the critical importance of selecting appropriate hybrids for silage production to optimize feed quality and livestock productivity.

The ensiling process led to a minor decrease in dry matter (DM) content (2.13%). This reduction in DM is primarily attributed to the fermentation process, wherein a portion of the dry matter is converted into gases and other fermentation by-products. The ensiling process typically involves the loss of water-soluble carbohydrates and volatile compounds, contributing to decrease in DM content. Conversely, the digestibility of maize silage showed improvement following the ensiling process. Key indicators of digestibility, including IVDMD, IVNDFD, and OMD, exhibited increases post-ensiling. This enhancement in digestibility is likely due to the fermentation-driven breakdown of complex carbohydrates into simpler, more accessible forms, thereby increasing the availability of nutrients for ruminants. Interestingly, the CP content remained stable throughout the ensiling process. Crude protein is a vital component of livestock nutrition, and its stability during ensiling is essential for maintaining the nutritional integrity of the silage. The preservation of CP content ensures that the protein needs of livestock are consistently met, contributing to the overall nutritional value of the silage. The observed variability among hybrids emphasizes the potential for selecting superior hybrids specifically suited for silage production. The combination of DM loss, improved digestibility, and stable CP content signifies a successful ensiling process that enhances the nutritional value of maize silage. Furthermore, the reduction in water-soluble carbohydrates confirms their utilization during fermentation, as an indicator of effective fermentation dynamics.

These findings highlight the significance of careful hybrid selection, the application of optimal ensiling techniques in producing high-quality silage and variation among the various nutritional quality parameters of silage. This, in turn, optimizes feed efficiency and supports enhanced livestock productivity. Future research should focus on identifying hybrids with superior fermentation characteristics and investigating the molecular mechanisms underlying these traits to further improve silage quality. The quality of silage cannot be measured by a single parameter; rather, it is the cumulative performance of various traits that determines overall silage quality. While DM loss should be minimized, crude protein content, which reflects the nitrogen present in the silage, serves as a critical indicator of both true protein and non-protein nitrogen. Given that maize silage is typically low in protein content (Khan *et al*., 2015), adequate of CP is crucial. Inadequate CP levels can impede the bacteria responsible for fermentation, ultimately affecting the silage's intake and digestibility by livestock.

### *Interrelationship among silage quality parameters:*

The correlation coefficient is a fundamental statistical measure in plant breeding, offering valuable insight into the nature and strength of genetic and non-genetic associations among traits (Dewey and Lu, 1959). A strong correlation between traits implies that improvement in one may simultaneously enhance or reduce another. In this study, correlation analysis among yield and quality traits was performed to unravel their interdependence and identify key traits contributing to superior silage performance. Pearson's correlation coefficients revealed meaningful relationships that can guide effective selection strategies in maize improvement programs (Fig 1).

DM was positively correlated (NDF (r = 0.58) and cellulose (r = 0.40), while TDF showed a positive correlation with CP (r = 0.53) and hemicellulose (r = 0.73), but a negative correlation with NDF (r = -0.67), ADF (r = -1), and ADL (r = -0.51). Additionally, DM was positively correlated with pH (r = 0.57), and ether extract (EE) was positively correlated with DM loss (r = 0.47), reflecting the influence of fermentation and lipid metabolism on silage preservation.

In previous study by Jancik *et al*. (2008), who demonstrated that higher CP levels were associated with reduced indigestible fiber content in grasses, emphasizing the antagonistic relationship between cell wall deposition and protein accumulation during plant maturation. The consistency of these findings across studies highlights the critical balance between structural and nutritional components in determining forage nutritive value, suggesting that selection for reduced fiber fractions can simultaneously enhance crude protein availability and digestibility in maize silage.

These positive correlations are attributed to the reduction in water-soluble carbohydrates as DM increases, affecting overall silage quality. As DM content rises above

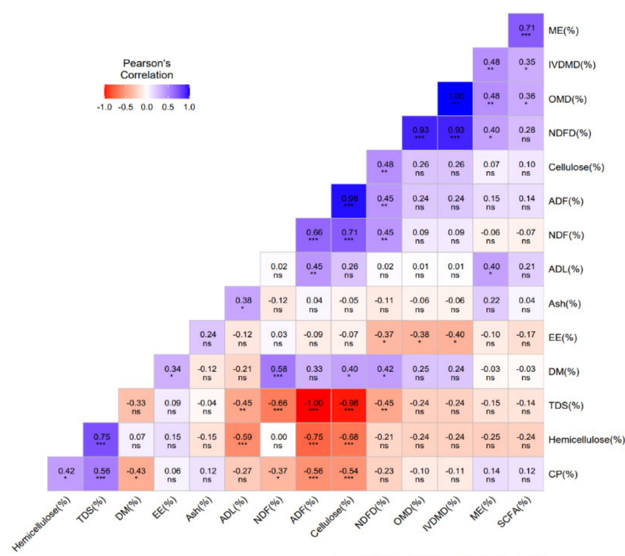


**Fig 1**. Correlation among the various studied traits contributing to the silage quality [TDF: Total dietary fiber; DM: Dry matter; EE: Ether extract; ADL: Acid detergent Lignin; NDF: Neutral detergent fiber; ADF: Acid detergent fiber; IVNDFD: In vitro neutral detergent fiber digestibility; OMD: Organic matter digestibility; NDFD: In vitro neutral detergent fiber digestibility; ME: Metabolizable energy; SCFA: Short-chain fatty acids]

40-45%, silage pH increases due to reduced metabolic water availability for lactic acid bacteria (Kung and Shaver, 2001). These findings provide valuable insights for breeders and animal nutritionists, enabling them to optimize silage parameters to enhance nutrient availability and energy intake for livestock.

***Parameters of variability:*** The success of a breeding program hinges on the genetic variability present within the population, as this variability facilitates the selection of desirable genotypes. Key metrics of variability, including the phenotypic coefficient of variation (PCV), genotypic coefficient of variation (GCV), heritability ($h^2$), and genetic advance as a percentage of the mean (GAm), were assessed for various traits (Table 3).

High PCV and GCV values (>20%) were observed for ADL (PCV = 31.75; GCV = 30.03), DM loss (PCV = 24.00; GCV = 23.81), and EE (PCV = 21.59; GCV = 20.75), indicating substantial genetic variability, a broad genetic base, and minimal environmental influence on these traits. These traits are primarily governed by additive genes, suggesting good potential for improvement through selection. Similar findings were reported by Naharudin *et al*. (2021) in studies of diverse maize crosses.

Moderate PCV and GCV (10-20%) were found for ash (PCV = 20.40; GCV = 18.59), ADF (PCV = 16.13; GCV = 15.14), cellulose (PCV = 16.62; GCV = 15.51), and hemicellulose (PCV = 14.88; GCV = 15.14). The small differences between PCV and GCV suggest a limited environmental impact, making phenotypic selection a reliable method. Lower PCV and GCV values were observed for DM (PCV = 8.97; GCV = 7.98), pH (PCV = 3.84; GCV = 3.30), and CP (PCV = 7.04; GCV = 6.61), indicating less variability and diversity for these traits among the hybrids.

Heritability estimates, ranging from 60.00 to 92.38%, were generally high for most traits, except DM, which exhibited moderate heritability (30-60%). High heritability coupled with high genetic advance was observed for DM loss (98.41%; 48.65%), ash (83.01%; 34.90%), ADF (88.15%; 29.30%), ADL (89.46%; 58.52%), EE (92.38%; 41.09%), cellulose (87.01%; 29.80%), and hemicellulose (65.86%; 20.20%). This indicates that these traits are under strong genetic control and can be effectively improved through selection.

The moderate heritability observed for DM suggests that environmental factors play a significant role in its phenotypic expression, making direct selection less effective. However, high heritability combined with moderate genetic advance was noted for traits like DM (79.00%; 14.65%), CP (88.04%; 12.77%), and NDF (87.94%; 13.83%), indicating potential for improvement. Low heritability coupled with low genetic advance was observed for traits like pH (74.01%; 5.80%) and days to maturity (72.20%; 6.52%), implying that selection may be less effective for these traits.

Understanding heritability and genetic advance is crucial for predicting the outcomes of selection and guiding breeding strategies. High heritability indicates that the traits are likely to be passed on to future generations, while genetic advance provides insight into the potential for improvement through selection. The combined analysis of these parameters suggests that breeding programs should focus on traits with high heritability and genetic advance to achieve substantial genetic gains.

**Table 3.** Variability parameters for the studied traits

| Traits* | CD | Sem | GCV | PCV | Heritability | GAm |
|---|---|---|---|---|---|---|
| DM loss (%) | 0.18 | 0.06 | 23.81 | 24.00 | 98.41 | 48.65 |
| Ammonia (%) | 0.22 | 0.01 | 8.06 | 9.01 | 80.00 | 14.87 |
| DM (%) | 2.70 | 0.92 | 7.98 | 8.97 | 79.00 | 14.65 |
| pH (%) | 0.17 | 0.06 | 3.30 | 3.84 | 74.01 | 5.80 |
| CP (%) | 0.49 | 0.17 | 6.61 | 7.04 | 88.04 | 12.77 |
| Ash (%) | 0.98 | 0.33 | 18.59 | 20.40 | 83.01 | 34.90 |
| ADF (%) | 3.76 | 1.26 | 15.14 | 16.13 | 88.15 | 29.30 |
| NDF (%) | 3.42 | 1.14 | 7.16 | 7.63 | 87.94 | 13.83 |
| ADL (%) | 0.84 | 0.28 | 30.03 | 31.75 | 89.46 | 58.52 |
| EE (%) | 0.31 | 0.10 | 20.75 | 21.59 | 92.38 | 41.09 |
| Cellulose (%) | 3.57 | 1.19 | 15.51 | 16.62 | 87.01 | 29.80 |
| Hemicellulose (%) | 5.34 | 1.79 | 12.08 | 14.88 | 65.86 | 20.20 |

DM loss: Dry matter loss; DM: Dry matter; CP: Crude protein; ADF: Acid detergent fiber; NDF: Neutral detergent fiber; ADF: Acid detergent lignin; EE: Ether extract

**Table 4.** Comparative analysis of silage *vs* fodder traits

| Traits | Fresh | | | Silage | | | Percent Change* |
|---|---|---|---|---|---|---|---|
| | Mean | SD | CV | Mean | SD | CV | |
| DM (%) | 32.63 | 2.61 | 8.01 | 31.94 | 2.64 | 8.26 | -2.13 |
| CP (%) | 9.39 | 0.79 | 8.38 | 9.40 | 0.74 | 7.90 | 0.15 |
| Ash (%) | 5.53 | 1.03 | 18.65 | 5.57 | 1.06 | 18.97 | 0.58 |
| ADF (%) | 32.88 | 5.34 | 16.25 | 32.58 | 5.37 | 16.49 | -0.94 |
| NDF (%) | 61.91 | 3.56 | 5.75 | 61.81 | 3.66 | 5.92 | -0.16 |
| ADL (%) | 3.83 | 1.15 | 29.87 | 3.94 | 1.13 | 28.67 | 3.91 |
| EE (%) | 2.24 | 0.53 | 23.59 | 2.17 | 0.51 | 20.58 | 1.50 |
| Cellulose (%) | 29.05 | 5.00 | 17.22 | 28.64 | 4.89 | 17.09 | -1.36 |
| Hemicellulose (%) | 29.03 | 4.20 | 14.46 | 29.24 | 3.98 | 13.61 | 0.82 |
| TDF (%) | 64.83 | 3.74 | 5.77 | 65.04 | 3.76 | 5.78 | 0.33 |
| OMD (%) | 61.07 | 3.59 | 5.88 | 67.90 | 2.39 | 3.52 | 6.83 |
| IVNDFD (%) | 45.1 | 6.84 | 17.13 | 50.12 | 4.97 | 9.69 | 10.90 |
| IVDM (%) | 61.69 | 3.38 | 5.49 | 68.24 | 2.27 | 3.33 | 8.66 |
| ME (%) | 7.25 | 0.30 | 4.16 | 7.60 | 0.35 | 4.59 | 4.21 |
| SCFA (%) | 0.72 | 0.05 | 6.54 | 0.721 | 0.03 | 4.50 | 0.14 |
| Ammonia (%) | | | | 0.25 | 0.39 | 9.53 | |
| pH | | | | 4.07 | 0.02 | 8.40 | |
| DM loss (%) | | | | 2.82 | 0.65 | 23.10 | |

*Sign indicates increase (+ or no sign) and decrease (-)

***Comparative quality analysis of fresh fodder vs. silage in maize:*** The comparison of nutritional composition between fresh and ensiled maize fodder revealed distinct variations in proximate and fiber fractions (Table 4). A slight reduction in DM (–2.13%) was observed after ensiling, likely due to fermentation losses. CP content remained nearly constant (+0.11%), while ash showed a minor increase (+0.15%), indicating stable mineral composition. Among fiber fractions, ADF (–0.94%), NDF (–0.16%), and cellulose (–1.36%) decreased slightly, whereas hemicellulose and TDF increased marginally (+0.82% and +0.33%, respectively).

A noticeable improvement was recorded in energy and digestibility related parameters: OMD (+6.83%), IVNDFD (+10.90%), IVDM (+8.66%), and ME (+4.21%), demonstrating enhanced fermentative quality and nutrient availability in silage. EE content also increased markedly (+1.27%), reflecting higher lipid preservation. Minor variations were noted in SCFA (+0.14%). Overall, the ensiling process improved the digestibility and energy potential of maize fodder, with minimal changes in protein and fiber fractions, confirming the effectiveness of fermentation in enhancing feed quality.

This analysis supports the efficiency of using fresh-dried samples for initial quality assessments in forage breeding programs. This approach offers significant advantages in terms of time and resource management. According to Karnatam *et al*. (2023), optimal silage quality parameters include DM (30-35%), pH (3.5-4.5), ash content (5-9%), ADF (30-35%), NDF (55-60%), ADL (2-4%), and EE (2-3%). Among the tested hybrids, JQPM1 emerged as the most promising with an IVDMD of 71.90%, closely followed by JH17026 (69.65%) and JH20209 (69.61%), all of them also exhibited high DM content (>31%). The study establishes that the selection of maize hybrids based on fresh fodder quality is a reliable strategy for ensuring superior silage quality and enhancing livestock productivity.

## Conclusion

The study highlights that maize hybrids with superior fresh fodder quality consistently produce higher-quality silage. Strong correlations between fodder and silage traits underscore the efficiency of using fodder composition as a selection criterion. This approach can streamline hybrid breeding and enhance livestock nutrition and productivity.

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