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Review Article

MECHANIZATION EFFICIENCY AND STORAGE STRATEGIES IN CORN SILAGE PRODUCTION: A REVIEW

Mehmet Bahadır[1,a,*], Mustafa Yıldırım[2,b], Ergin Topbaş[3,c], Osman Özbek[4,d]

[1] *Konya Technical University, Vocational School of Technical Sciences, Department of Machinery and Metal Technologies, Konya, Türkiye.*

[2] *Selçuk University Institute of Sciences Agricultural Machinery and Technologies Engineering, Konya, Türkiye*

[3]*Selçuk University Institute of Sciences Agricultural Machinery and Technologies Engineering, Konya, Türkiye*

[4]*Selçuk University Department of Agricultural Machinery and Technologies Engineering, Konya, Türkiye*

**Corresponding Author:*
E-mail: mbahadir@ktun.edu.tr

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a: ORCID 0000-0002-5071-5085 b: ORCID 0009-0001-9705-1327, c: ORCID 0009-0005-0816-0978 d: ORCID 0000-0003-0034-9387

ABSTRACT. This study examines the mechanization of corn silage production and various silage storage methods, aiming to enhance the efficiency and sustainability of high-quality feed production in the livestock sector. The importance of corn silage, optimal harvest timing, silage machinery, and different storage techniques (traditional, cylindrical bale, and tube silage methods) are analyzed in detail. The research evaluates the operational efficiency, fuel consumption, performance, and economic costs of each method through a comparative approach. The findings indicate that the tube silage method offers high capacity and efficiency for large-scale operations, while the cylindrical bale method excels in compaction quality and nutrient preservation. The traditional method, due to its low cost and simplicity, remains suitable for small-scale farms. Additionally, the role of corn silage in animal nutrition, optimization strategies for production processes, and trends in corn production in Türkiye are discussed. This study provides scientific insights into the mechanization and storage processes of corn silage production, offering guidance for producers and policymakers. The results contribute to improving feed quality, minimizing losses, and promoting sustainable agricultural practices.

Keywords: *animal nutrition, corn silage, efficiency, mechanization, silage storage methods*

MISIR SİLAJI ÜRETİMİNDE MEKANİZASYON ETKİNLİĞİ VE DEPOLAMA STRATEJİLERİ

ÖZET. Bu çalışma, hayvancılık sektöründe yüksek kaliteli yem üretiminin verimliliğini ve sürdürülebilirliğini artırmayı amaçlayarak, mısır silajı üretiminin mekanizasyonunu ve çeşitli silaj depolama yöntemlerini incelemektedir. Mısır silajının önemi, optimum hasat zamanlaması, silaj makineleri ve farklı depolama teknikleri (geleneksel, silindirik balya ve tüp silaj yöntemleri) detaylı olarak analiz edilmiştir. Araştırma, her yöntemin operasyonel verimliliğini, yakıt tüketimini, performansını ve ekonomik maliyetlerini karşılaştırmalı bir yaklaşımla değerlendirmektedir. Bulgular, tüp silaj yönteminin büyük ölçekli işletmeler için yüksek kapasite ve verimlilik sunduğunu, silindirik balya yönteminin ise sıkıştırma kalitesi ve besin maddesi korunmasında üstün olduğunu göstermektedir. Geleneksel yöntem, düşük maliyeti ve basitliği nedeniyle küçük ölçekli çiftlikler için uygun olmaya devam etmektedir. Ayrıca, mısır silajının hayvan beslenmesindeki rolü, üretim süreçleri için optimizasyon stratejileri ve Türkiye'deki mısır üretimindeki eğilimler tartışılmıştır. Bu çalışma, mısır silajı üretiminin mekanizasyon ve depolama

süreçlerine bilimsel bilgiler sunarak üreticilere ve politika yapıcılara rehberlik sağlamaktadır. Sonuçlar, yem kalitesinin iyileştirilmesine, kayıpların en aza indirilmesine ve sürdürülebilir tarım uygulamalarının teşvik edilmesine katkıda bulunmaktadır.

Anahtar kelimeler*:* *hayvan beslenmesi, mısır silajı, verimlilik, mekanizasyon, silaj depolama yöntemleri*

INTRODUCTION

The primary purpose of agricultural activities is to meet human nutritional needs. A significant portion of these needs, particularly protein requirements such as meat and milk, is supplied by animals. In livestock enterprises in Türkiye, feed costs constitute a major share (50% to 70%) of total production expenses [1]. Accordingly, integrating precision agriculture tools (especially remote sensing–based monitoring of forage yield and quality) can strengthen decision-making for harvest timing and ration quality at the farm scale [2]. For economic and profitable livestock production, it is essential to increase the availability of roughage resources [3]. Regardless of the animals genetic potential and environmental conditions, it is not possible to achieve the desired high productivity unless proper care and feeding are ensured. In this context, besides genetic capacity, nutrition plays a critical role [4]. During periods when fresh forage is not available, especially in winter, the only roughage that can be offered to animals in an economical and nutritive manner to sustain productivity is silage. The controlled "pickling" of fresh forages is referred to as ensiling, and the resulting product is called silage.

Various grasses and forage crops consumed by animals are harvested, chopped, and preserved under anaerobic conditions, preventing contact with air. In this way, their nutritional value can be maintained—indeed, in some cases enhanced through lactic acid fermentation. As a result, high-quality feed can be supplied to animals even in periods when fresh forage is unavailable. Farmer experiences and research on dairy production systems indicate that maize silage is not a substitute for pasture but can be profitable when used as a supplement [5]. It has been reported that maize silage provides the greatest benefit when it is used to compensate for feed shortages caused naturally (e.g., summer droughts) or by management strategies such as extending the lactation period or increasing stocking density [6, 5]

The basic principle of ensiling is the fermentation of moisture-rich roughage by lactic acid bacteria in an anaerobic environment. Among the crops suitable for silage, maize is considered the most important, and the highest-quality silage is obtained from maize. When maize is used for silage, the entire above-ground biomass of the plant can be utilized.

MAIZE

Maize is a warm-season annual cereal vital for both human and animal nutrition, used as grain or silage (Fig. 1). To achieve high yields, five parameters are critical: soil preparation, sowing method, irrigation, fertilization, and harvest timing.



Fig. 1. *Maize plant*

Soil Preparation and Sowing

Before spring sowing, the field should be leveled and cultivated with a cultivator-harrow to create a suitable seedbed. For optimal germination, soil temperature should be around 12–13 °C (typically April in Central Anatolia). As a row crop, maize is best sown with precision pneumatic drills. Row spacing should be 70 cm, with intra-row distances of 13–15 cm depending on variety and fertility. A density of 80.000–100.000 plants per hectare, placed 5–6 cm deep, is ideal. For silage, the seed rate varies between 40–60 kg ha^{-1} based on kernel size.

Irrigation

To prevent water stress (often indicated by leaf rolling) irrigation must be timely. If sowing moisture is low, irrigate to ensure uniform emergence. The critical growth stages requiring peak water are:

- Initial growth (plant height 10–15 cm).
- Following earthing-up and fertilization.
- 7–10 days before tassel emergence (the stage of highest demand).
- The milk stage of kernel development.

Fertilization and Harvest

Applying 10–20 tons ha^{-1} of manure in autumn improves soil structure. At sowing, 100–150 kg ha^{-1} of DAP is recommended. Top-dressing requires 50–60 kg ha^{-1} of ammonium nitrate, with nitrogen split between sowing and the earthing-up stage.

Silage should be harvested at 65–70 % moisture, levels outside this range lead to spoilage. The ideal window is when kernels approach physiological maturity but can still be crushed by teeth. Under optimum conditions, average yields reach 60–70 tons ha^{-1} (Fig. 2).

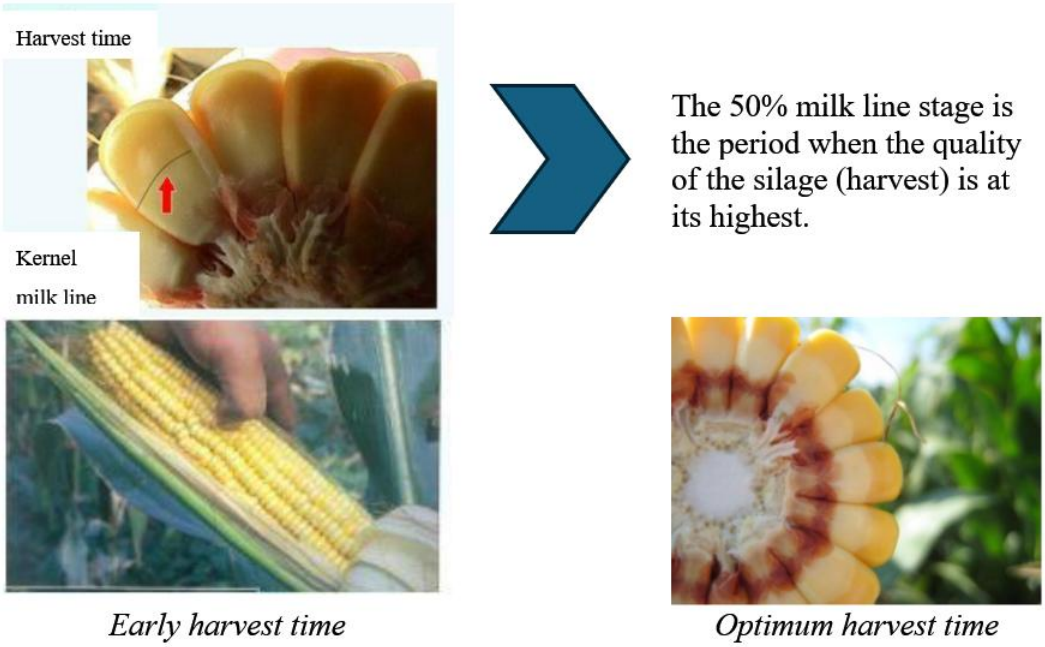


Fig. 2. *Optimal Harvest Period for Maize*

Maize Cultivation Areas

In Türkiye, the maize cultivation areas averaged approximately 0.68 million hectares during the 2015/16 period. In the 2023/24 season, however, these areas exhibited a 5% increase compared to the preceding period, expanding to 0.96 million hectares (Fig. 3).

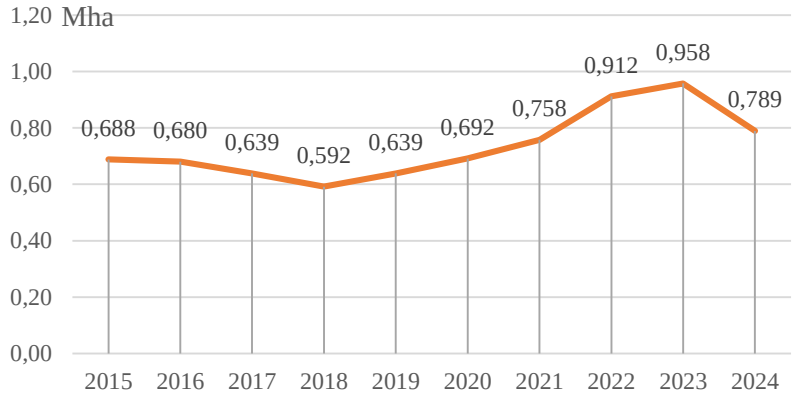


Fig. 3. *Maize (grain) cultivation area between 2015 and 2024* [7]

As of 2024, the top ten provinces with the largest maize cultivation areas in Türkiye are presented in Table 1.

Table 1. *Provinces with the highest maize cultivation* [8]

Cities	Corn planted area (ha)	%
Konya	158.993,9	20,14%
Şanlıurfa	105.951,4	13,42%
Adana	79.785,1	10,11%
Eskişehir	38.725,1	4,91%
Karaman	38.212,5	4,84%

Maize Production

In Türkiye, maize production, which was 6.4 million tons in 2015, declined to 5.7 million tons in 2018. In 2019, however, production increased by 5.3%, reaching 6 million tons. As shown in Table 2, a total output of 9 million tons was achieved between 2023 and 2024, with an average yield of 93.944 kg per hectares. When assessed on a provincial basis for the year 2023, the provinces accounting for approximately 50% of the national production were, in order, Konya, Şanlıurfa, Adana, Mardin, and Karaman (Fig. 4).

Table 2. *Annual maize production volumes in Türkiye* [8]

Years	Production (ton)	Yield ($kg.ha^{-1}$)
2015	6.400.000	93,000
2016	6.400.000	94,115
2017	5.900.000	92,320
2018	5.700.000	96,300
2019	6.000.000	93,922
2020	6.500.000	93,981
2021	6.750.000	89,022
2022	8.500.000	93,214
2023	9.000.000	93,944

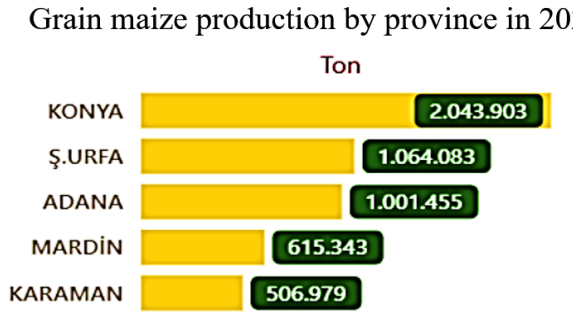


Fig. 4*. The top five provinces in Türkiye in terms of maize (grain) production in 2023* [7]

As can be observed from Fig. 5, the self-sufficiency level in maize production in Türkiye, based on an evaluation of the past decade, was 83% in meeting domestic demand.

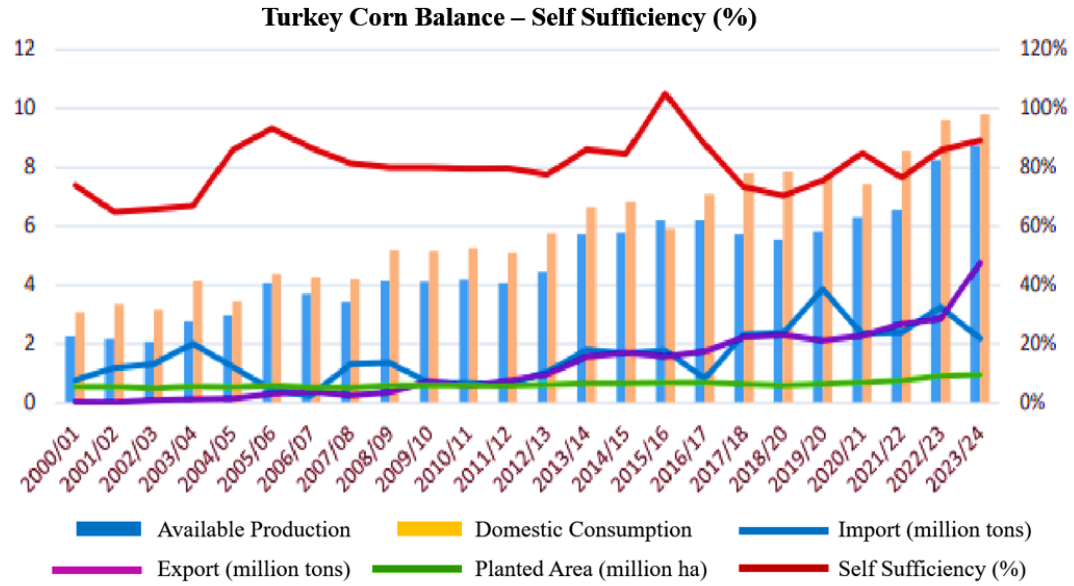


Fig. 5. *Maize balance and self-sufficiency level in Türkiye* [9]

As illustrated in Fig. 6, compound feed production has increased fivefold over the past two decades. As of the 2023/24 season, the feed industry accounts for 88.5% of maize utilization.

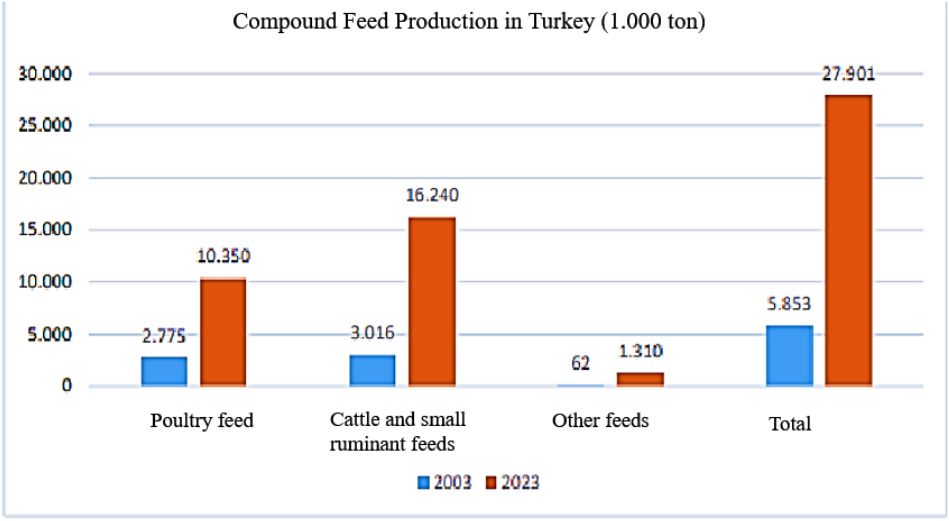


Fig. 6. *Compound feed production in Türkiye* [10]

Türkiye's total compound feed production has increased nearly fivefold over the past 20 years, rising from 5.9 million tons to 27.9 million tons. When examined by feed type, this increase corresponds to a 3.7-fold growth in poultry feed and a 5.4-fold growth in ruminant feed [10]. According to data from the Food and Agriculture Organization (FAO), the annual maize production figures of the world's top ten countries since 2015, along with the corresponding graphical representation, are presented in Fig. 7.

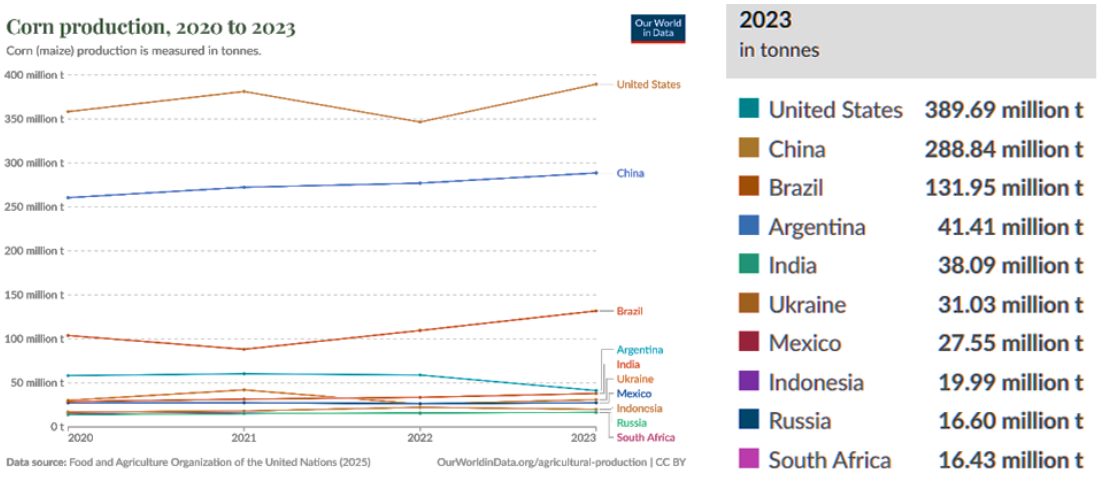


Fig. 7. *Maize production data of the top ten countries worldwide by year* [11]

Global maize production has reached approximately 1.24 billion tons. The United States (~390 million tons) and China (~290 million tons) together account for more than half of the world's maize output. These countries are followed by Brazil with a production level of about 132 million tons. Argentina and India rank fourth and fifth, respectively. Due to drought, Argentina reduced its production in 2023 (2022: 59.04 million tons → 2023: 41.41 million tons). Similarly, Ukraine's production declined as a result of the war

in 2022 (2021: 42.11 million tons → 2022: 26.19 million tons). According to FAO data, the average maize yields per hectare of the top ten countries worldwide since 2015, together with the corresponding graphical representation, are presented in Fig. 8.

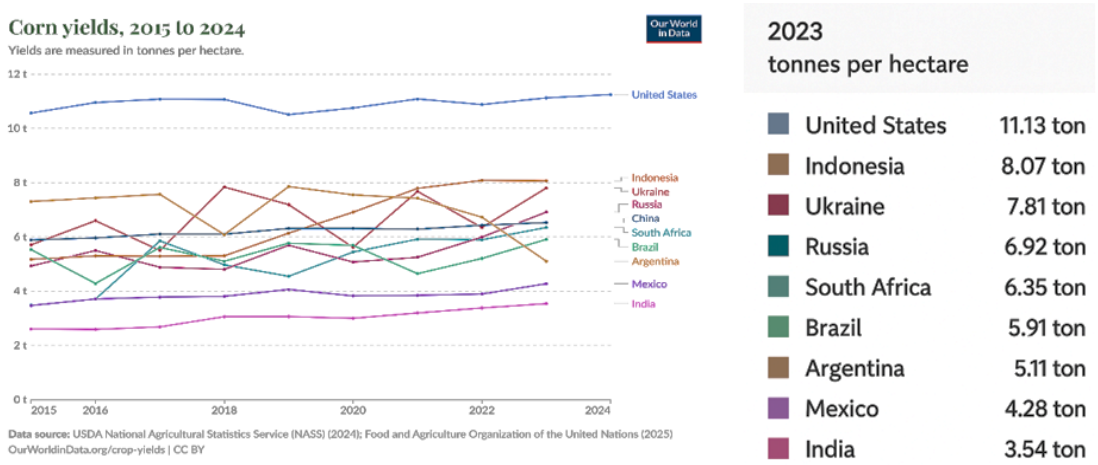


Fig. 8. *Average maize yield per hectare of the top ten countries worldwide by year* [11]

The United States ranks first in terms of average maize yield per hectare with 11.13 tons. Indonesia holds the second position with 8.07 tons, while Ukraine (7.81 tons) and Russia (6.92 tons) occupy the third and fourth ranks, respectively, despite the adverse impacts of war.

MAIZE SILAGE

Silage is a high-nutrient feed obtained by fermenting forage crops with high moisture content under anaerobic conditions through the activity of lactic acid bacteria. Maize silage is produced by harvesting the maize plant at approximately 35–40 % dry matter content, during the milk stage of the cobs, followed by chopping, compacting, and storing under anaerobic conditions to enable fermentation (Fig. 9). Owing to its high content of readily degradable carbohydrates and its favorable buffering capacity, maize is considered the most easily ensiled forage crop. In addition, it serves as an indispensable roughage source due to its high energy content and palatability for ruminants. In addition, it constitutes an indispensable roughage source due to its high energy content and its high palatability for ruminants [12].



Fig. 9. *Maize Silage*

Importance of Maize Silage

High-quality maize silage, owing to its high protein and energy content, constitutes an excellent feed resource in dairy and beef cattle production. In addition to its nutritional value, maize silage plays a significant role as a cost-effective source of energy in animal feeding.

The target values for high-quality maize silage are as follows: dry matter content between 28–35%, an energy level of 10.8 MJME per kg of dry matter, a protein content of 7–8%, and a pH level ranging from 3.8 to 4.5 [13].

There are six essential rules for producing high-quality silage:

a. Selecting an appropriate variety for silage

- A suitable maize hybrid for silage should possess the following characteristics:
  - High energy content
  - High grain yield
  - Optimum dry matter yield
  - Grain-to-stover ratio of 40:60
  - High digestibility

b. Silage harvesting must be performed at an optimal moisture content

The most practical method for determining the optimal harvesting time is monitoring the kernel milk line. Recent extension guidance emphasizes harvesting corn silage around 62–65% moisture (35–38% DM) and prioritizing rapid harvest, aggressive packing, and airtight sealing to protect fermentation quality and farm profitability [14]. Beyond visual maturity indicators, an image-processing + ANN approach predicted wet-basis moisture content of maize (and beans) from dimensional changes with about 82% model efficiency, indicating a scalable pathway for rapid moisture estimation workflows [15]. When the milk line reaches the midpoint of the kernel, the energy and silage yield potential of the maize plant are at their maximum, and the plant moisture content is around 65–70% (Fig. 10). At this stage, compaction of the silage can be achieved more effectively. The dry matter content of maize silage at this point typically ranges between 30–35%.

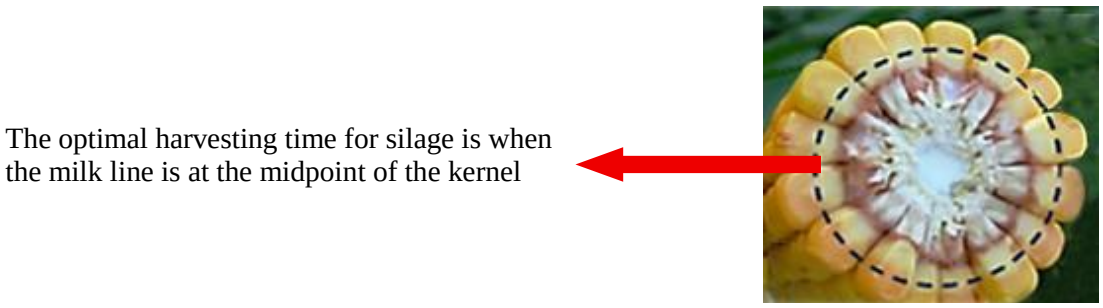


Fig. 10. *Determining the harvesting time of silage maize*

c. Sharpening the Blades of the Forage Harvester and Harvesting at an Appropriate Height

The cutting height of maize from the soil surface affects both the quality and the digestibility of the silage. Typically, the cutting height for silage is around 15 cm above ground level. At this height, silage yield reaches its maximum. However, as the cutting height increases, for instance to 20–25 cm, silage yield decreases.

d. Rapid Transportation of the Crop to the Storage Site After Harvesting

While harvesting continues in the field, another trailer should be used to rapidly transport the harvested material to the storage site. Upon arrival, the silage should be spread evenly on the storage surface at a thickness not exceeding 15–20 cm and compacted immediately. The silo should be completely filled within the same day, and the process must be finalized within 24 hours, after which the surface should be tightly sealed.

e. Use of Silage Additives

Additives are employed to improve silage prepared under suboptimal or unfavorable conditions. The most commonly used additives include bacterial inoculants, non-protein nitrogen compounds, enzymes, salts, and organic acids.

f. Proper Compaction and Covering of Silage

One of the most critical rules for producing high-quality silage is ensuring maximum compaction using the heaviest available tractors or machinery. Following compaction, the silage surface should be covered with an opaque plastic sheet (Fig. 11).



Fig. 11. *Compaction and Covering of Silage*

Benefits of Silage Production

- It contributes to the adequate and cost-effective feeding of animals during the winter months, when the shortage of succulent and green forages is most evident.
- Problems associated with forage storage and related costs are minimized.
- Silage can be preserved for long periods without any loss of nutritional value, and it is readily consumed by animals.
- Since silage crops vacate the field earlier, additional time is made available for the cultivation of subsequent crops.
- Unlike dry hay and straw bales, which present a fire hazard, fermented feeds (silage) carry no such risk.

Considering these advantages, maize silage has become the most preferred feed in cattle fattening systems. Particularly in countries advanced in livestock production such as the United States, France, the Netherlands, and Germany, the feeding of beef cattle is largely based on maize silage supplemented to address protein deficiencies. The daily silage requirements of different animal categories are presented in Table 3.

***Table 3**. Daily silage requirements of animals* [16]

Livestock	**Silage requirement (kg.day^{-1})**
Dairy cows	20 - 30
Heifers	10 - 12
Dairy calves	5 - 6
Beef calves	5 - 10
Sheep and Goats	4 - 6

In recent years, the numbers of cattle and small ruminants in Türkiye have been presented in Table 4.

***Table 4.** Livestock population and its changes in Türkiye* [16]

	2023 (Head)	**2024 (Head)**	**Variation**
Cattle	16.421.256	16.824.208	+ %2,5
Water Buffalo	161.749	162.051	+ %0,2
Sheep	42.060.470	44.080.584	+ %4,8
Goats	10.302.940	10.822.084	+ %5,0

Maize Silage Harvesting Machines

Maize silage harvesting machines are agricultural implements that cut the maize plant as close as possible to the soil surface, chop it into fine slices within the cutter mechanism of the machine, and subsequently transfer it to a trailer located at the rear (Fig. 12). There are two main types of maize silage harvesters: tractor-mounted units, which are powered by the tractor, and self-propelled forage harvesters.



***Fig. 12.** Operating principle of a maize silage harvester*

Tractor-drawn maize silage harvesters are attached to the tractor via the three-point hitch system and operate by receiving power from the power take-off (PTO). Although these machines are specifically designed for maize silage, they can also be utilized in the ensiling of other crops with similar morphological structures, such as sorghum and sunflower. Depending on their configuration, they may harvest one, two, or three rows simultaneously, or they may operate independently of row alignment (Fig. 13).



Single-row harvester twin-row harvester 3-row / 4-row harvester

Fig. 13. *Tractor-drawn maize silage harvesters*

Self-propelled silage harvesters are machines manufactured exclusively for this purpose (Fig. 14). Although these machines offer high operational capacity and ease of use, their high cost poses a significant challenge for farmers in terms of affordability.



Fig. 14. *Self-propelled silage harvesters*

In Türkiye, the use of silage harvesters has increased in parallel with the rise in maize silage production. Fig. 15 illustrates the number of maize silage harvesters and their changes over the years.

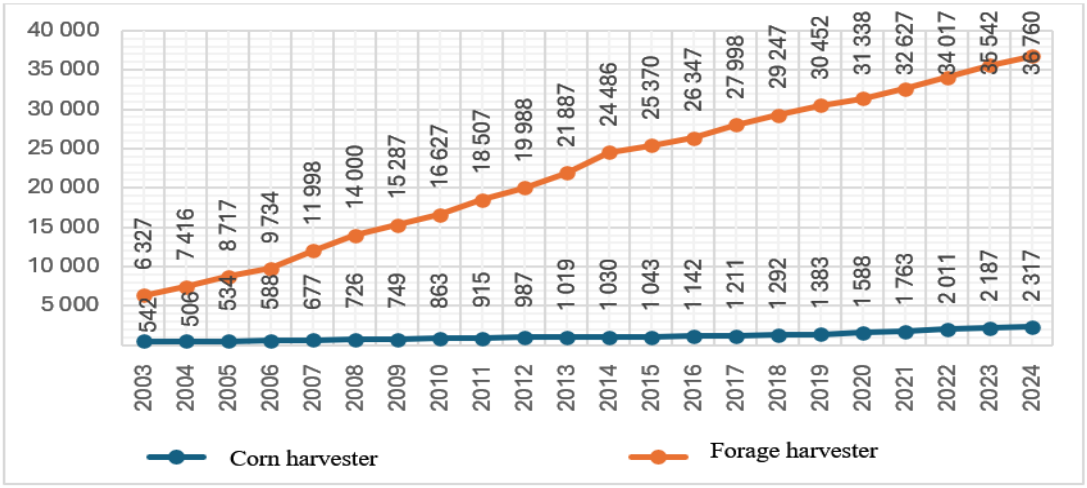


Fig. 15. *Number of maize harvesters and silage harvesters in Türkiye by year* [8]

The maximum theoretical capacity values of maize silage harvesters for chopped maize material with approximately 75% moisture content and 12.7 mm particle length are around 50 tons per hour [17]. As the operating speed of the machine decreases and the rotational speed of the chopping knives increases, the plant material is fragmented into finer particles. Conversely, when the machine operates at higher speeds with lower knife rotation, the particle length of the chopped material increases [18].

The power requirement of silage harvesters depends on the working conditions of the machine, the type of crop harvested, and the technical features of the chopping unit. The total power demand of a silage harvester consists of four main components [19]:

a) The power required for the tractor's own propulsion.
b) The power take-off (PTO) requirement of the silage harvester.
c) The traction power necessary for the movement of the silage harvester.
d) The power needed to pull the silage trailer.

Recent studies have moved beyond component-based descriptions and proposed data-driven approaches to estimate PTO power demand. For instance, machine-learning models have been used to predict PTO shaft power of disc-type maize silage harvesters under varying operating conditions, enabling decision support for energy-efficient operation [20]. The first step in silage preparation is cutting the maize plant from its stem and chopping it into suitable lengths. Properly sized chopped maize becomes ready for ensiling. The target particle length and shape during chopping are critical for the quality of the final product. The equipment performing the cutting action, which separates the plant stem into pieces, is referred to as the "knife." A functional knife consists of two main components: the knife tip and the knife blade [21].

When chopping knives are properly sharpened, the friction force on the knife surface is reduced, thereby decreasing the cutting force requirement. With sharp knives, the applied cutting action generates forces perpendicular to the knife movement on the plant stem, creating sufficient shearing force for effective fragmentation [21]. If sufficient clearance is maintained between the cutting knife and the counter-knife, and the knives are sharp, the plant is cut cleanly rather than torn. However, if the cutting knife becomes blunt, even with adequate clearance, the plant material tends to be torn apart rather than cleanly cut, which is undesirable. For this reason, the cutting-edge angle of the knife must

not exceed a certain threshold. Accordingly, maize silage harvesters are equipped with a grinding system that maintains knife sharpness as the cutting edges become worn [21].

The chopping mechanism consists of the knife and counter-knife. The clearance between the two should not be less than 0.5 mm and should not exceed 1 mm. If this clearance increases to more than 1.5 mm, the required power doubles (Güner, 1998). Field measurements on a single-row disc silage machine showed that increasing knife–counter-knife clearance from 1→3 mm and 3→5 mm increased average fuel consumption by 8.86% and 29.89%, respectively, while the lowest fuel consumption was obtained at the 3 mm clearance–low speed combination [22].

SILOS AND ENSILING METHODS

Silo

Since green forages rich in water content are not available outside the summer season, they must be preserved and stored during periods of abundance. The process of storing or preserving chopped forages is known as ensiling.

The size of the silo depends on the number of animals, the quantity of forage to be ensiled, and the duration of feeding. For small-scale farms, constructing several small-capacity silos provides advantages in terms of both construction and feeding practices. Silos should generally be located near the barn and designed to allow easy filling and unloading of the material.

Ensiling Methods

Forage crops can be ensiled through different methods. Currently, ensiling methods are generally categorized as traditional and commercial silage-making techniques.

Traditional Silage-Making Method

Following the harvesting of forage crops using silage harvesters, the material is piled in heaps, compacted with heavy tractors, and then covered with plastic sheets to exclude air (Fig. 16). This method, also known as the surface silo method, is simple and cost-effective. The capacity and number of above-ground silos covered with plastic in a given farm depend on factors such as herd size, the area cultivated with silage crops, and production levels. The silo location should be selected close to the feeding area. Furthermore, protective measures should be taken to prevent animals with hooves from damaging the plastic-covered silos.



Figure 16. *Above-ground heap silo*

For silo construction, an area with a width of 4–5 meters and a length suitable for the quantity of material to be stored is prepared. The silo height should be between 1–2 meters, enabling efficient compaction by a tractor. After the forage material is heaped and

compacted in layers, the surface is entirely covered with a high-quality, durable plastic sheet that is resistant to tearing. The edges of the cover are extended and sealed with a 15–20 cm layer of soil. This soil layer applies pressure on the silo edges, effectively preventing air infiltration. If the applied pressure is insufficient, old vehicle tires or sand-filled weight bags may be used to reinforce the cover. Once filling is complete, a drainage channel of 20–25 cm depth is dug around the silo to protect the base from rainfall.

The traditional method of silage making can also be carried out in other forms, such as silage pits and silage bunkers. Today, silage pits are less commonly preferred, whereas silage bunkers are more widely used depending on the herd size and the scale of the farm. The number of animals on the farm and the daily silage consumption determine the width of the bunker, the wall height, and the overall length required to provide sufficient feed throughout the year. The wall height of a silage bunker should range between 2.5 and 4.5 meters, while its width should not be less than 6 meters. As in the traditional method, the silage in bunkers must be compacted and covered with a protective plastic sheet (Fig. 17).



Fig. 17. *Silage bunker and silage preparation*

Commercial Silage-Making Methods

Commercial silage-making methods are classified into two types: the cylindrical bale silage method and the tube silage method.

Cylindrical Bale Silage Method

Following the harvesting stage, the chopped forage is transported via conveyor wagons to a baling and wrapping machine, where it is compacted into bales and wrapped with plastic film.

Bale silage was first introduced in the 1970s in Australia and New Zealand. With the advancement of petrochemical plastics (films), this method became feasible. At that time, silage was commonly stored in bags; however, due to limited technical capacity, compaction could not be fully achieved manually, and the air inside the bags could not be sufficiently removed. In modern practice, compaction is performed mechanically. After compaction, bales are wrapped in 4–6 layers of specially developed plastic films (Fig. 18).



Fig. 18. *Wrapping of compacted bales with plastic film*

Recent developments in silage films and innovations in harvesting machinery have facilitated the preparation and baling of forage, contributing to the widespread adoption of this method.

The advantages of bale silage can be summarized as follows:

- The feed quality of bale silage is at least equivalent to, and often superior to, that of surface silos.
- Easier mechanization, offering convenience in storage and feeding.
- Lower capital investment requirements.
- Reduced transportation costs from field to storage.
- Less dependence on weather conditions, making preparation easier under suboptimal wilting conditions.
- Marketability during periods when green forage is scarce.
- Lower dry matter losses during preparation and storage.

Tube Silage Method

The tube silage method involves transferring chopped forage into a tube silage machine, where it is compacted and packaged in a continuous tunnel-like form. Unlike bale silage, in this method, the forage is preserved as a single, larger mass. In tube silage, the chopped material is ensiled within a long polyethylene tube using a machine equipped with a high-speed rotor that ensures effective compaction (Fig. 19).



Fig. 19. *Tube silage production*

In tube silage production, the machine operates by attaching an elastic polyethylene tube with a diameter of 2.7 m at the outlet where the toothed rotor is located. Among silage-making methods, the tube silage technique requires the highest feeding rate. To ensure effective compaction of the material, the chopped forage must be delivered smoothly and continuously into the bunker unit of the machine (Fig. 20). Achieving this requires intensive harvesting and transportation operations. Consequently, this method

necessitates the use of significantly higher-capacity harvesting machinery and transport vehicles compared to other methods.



Fig. 20. *Continuous filling process of the bunker unit in a tube silage machine*

EVALUATION OF THE MANAGERIAL VALUES OF ENSILING METHODS

Studies conducted on livestock enterprises have indicated that farms producing their own silage are approximately 50% more profitable compared to those purchasing silage externally [23]. In a study by Tuvanç and Dağdemir [24], it was reported that silage maize producers who predominantly rely on their own labor force and Factors such as tractor power cultivate their own land achieve higher economic profitability. Furthermore, when seed subsidies and support payments per hectare are taken into consideration, silage maize cultivation was concluded to provide farmers with higher income.

In light of these findings, the managerial values of enterprises employing different silage-making methods are presented in Table 5.

Table 5. *Results of managerial analyses of enterprises by silage-making method* [25]

	Methods of silage feed preparation		
	Traditional methods	**Round bale**	**Silage tube**
HARVEST			
Area	1.264 ha	0.481 ha	13.044 ha
Total material	50714 kg	26255 kg	713.4 t
Number of trailer trips	16	9	64
Transportation fuel consumption	5.81 L	2.21 L	228.28 L
Harvest duration	489.28 min.	311.03 min.	387.45 min.
Total fuel used in harvest	4.42 L	1.68 L	339.14 L
SILOING			
Silo height	792 mm	-	

Number of passes during compaction	221	-	-
Compaction distance	1332 m	-	-
Compaction time	135.56 min.	-	-
Number of bales	-	26 unit	-
Baling time	-	2.05 min.	-
Net wrapping time	-	0.55 min.	-
Film wrapping time	-	0.82 min.	-
Total siloing time	-	89 min.	-
Roto-press time	-	-	324.02 min.
Total fuel used in siloing	0.88 L	1.64 L	100.44 L
Total system fuel consumption	11.11 L	5.3 L	667.86 L

When the traditional method is considered, the annual operational values are presented in Table 5., assuming the use of two trailers and a single-row maize silage harvester. Based on these data, the time required to fill one trailer was 32 minutes. The active transport duration of a trailer—including travel to the silo and return to the harvesting field—was 6 minutes. At the silo site, unloading the chopped material hydraulically took 2 minutes. The empty trailer returning to the field waited 23.95 minutes for the other trailer to be filled [27]. Using the traditional method, silage maize was harvested within a single day. The harvesting of 1.264 ha required 489.28 minutes. A total of 50,714 kg of forage was compacted within 135.56 minutes, consuming 5.81 L of fuel for transportation. The total fuel consumption for transport and ensiling was 11.11 L.

Compared to the traditional method, the cylindrical bale method requires higher mechanization; therefore, alignment between operational values and process chains is of greater importance. To reduce the idle time of the baling and wrapping machine, harvesting capacity was doubled by using two single-row maize silage harvesters. In this method, 0.481 ha of land was harvested, and in 311.03 minutes, 26,255 kg of forage was chopped and transported in 9 trailer trips. The material was baled by the cylindrical baler and subsequently wrapped with plastic film by the wrapping unit of the same machine. To transfer the chopped forage into the baler bunker, a tractor equipped with a loader was used. A total of 26 bales were prepared within 89 minutes. For proper stacking of the bales, an additional tractor equipped with a clamp was employed. In this system, 26.25 tons of material were baled with a total fuel consumption of 5.53 L.

The tube silage method requires a significantly more intensive material flow compared to the other two methods. Its mechanization demands are considerably higher. Thus, harvesting machines and transport vehicles must not only be of high capacity but also function in harmony. Under these conditions, the managerial values of the tube silage method were notably higher than those of the other methods. To ensure continuous compaction of chopped silage within the tube, three trucks were employed. Owing to the high capacity of self-propelled forage harvesters, trailers could not be used. In this study, four tubes were prepared, and a total of 13.044 ha were harvested using self-propelled silage harvesters. The harvested area, product quantities, and operational times associated with the four tubes are presented in Table 5.

CONCLUSIONS AND RECOMMENDATIONS

This review consolidates corn silage mechanization and storage strategies into a single, end-to-end operational framework linking (i) harvest timing and crop moisture management, (ii) machine settings and energy demand, (iii) transport–logistics coordination, and (iv) storage/packaging choices and associated losses. Beyond summarizing prior studies, the manuscript's original contribution is the decision-oriented synthesis that connects method selection (traditional bunker/heap, cylindrical bale, tube) to measurable managerial indicators (worked area, throughput, logistics intensity, fuel use, and process time) and interprets these indicators under Türkiye's production realities (rising maize production/cultivation footprint, feed-sector demand pressure, and the predominance of cost-sensitive livestock systems).

From an operational standpoint, the comparative managerial evidence indicates that method differences do not arise only from storage geometry; they primarily emerge from system configuration (harvester capacity, number/type of transport units, and continuity of material flow). Tube silage is a high-throughput industrial workflow requiring synchronized high-capacity harvest and hauling; cylindrical bale silage is a quality and flexibility-centered workflow (portion-based, manageable units, strong compaction potential); and traditional systems remain a low-capex, low-complexity option that can be rational for smaller farms where equipment availability and coordination capacity are constrained. Therefore, the "best" method in Türkiye is not universal; it is scale-, distance-, and coordination-dependent, and should be evaluated as a logistics system rather than a single machine choice.

Türkiye-Specific Implications

Türkiye's livestock sector operates under high feed-cost pressure; consequently, improvements in silage efficiency and preservation quality translate directly into farm profitability and supply resilience. Given the regional concentration of maize cultivation and production, method choice should be aligned with regional field sizes, haul distances, labor availability, and access to contractor services/cooperatives. In particular, tube systems become financially defensible when high utilization and continuous operation can be guaranteed (large areas, short harvest windows, and reliable hauling capacity), whereas bale systems can be strategically valuable for farms prioritizing quality preservation, flexible feeding logistics, and risk management (weather variability, distributed storage, and marketing potential where relevant).

Recommendations for practice and policy

1. Adopt moisture- and timing-driven harvest management: Standardize harvest decisions around crop moisture/DM targets and rapid sealing/packing discipline; integrate scalable monitoring (e.g., remote sensing–supported yield/quality awareness) to improve timing and reduce losses at the farm scale.
2. Treat machine setup as an energy KPI lever: Maintain knife sharpness and proper knife–counter-knife clearance; incorporate routine checks as a formal operating procedure to control fuel consumption and chopping quality.

3. Design the harvest–transport chain as a synchronized system: For high-capacity workflows (especially tube), plan vehicle count, loading/unloading sequence, and buffer strategy to minimize idle time; prioritize transshipment/coordination solutions where feasible to improve effective capacity without proportionally increasing fuel use.
4. Select storage method by "scale × logistics × capital" rather than habit:

    - Small and resource-limited farms: optimize traditional bunkers/heaps with strict compaction and sealing protocols.
    - Quality-focused or coordination-limited farms: cylindrical bales can provide robust compaction and flexible handling.
    - Large-scale and contractor/cooperative-enabled operations: tube systems can compress the harvest window and increase throughput when continuity is ensured.

5. Policy action in Türkiye: Encourage shared machinery pools/contracting markets for high-capacity silage chains, operator training on compaction/sealing, and management of plastic-film waste streams to reduce environmental burden and improve sustainability outcomes

Future Research Agenda

The feasibility of such decision support tools has been demonstrated in international contexts. Busato et al. [26] developed a simulation-optimization model for silage harvesting logistics that determines the optimal number of transport units under time and cost constraints. Their tool, validated with field trials, minimizes total operational costs by synchronizing harvester capacity, trailer travel time, and silo unloading efficiency. This approach is directly transferable to Türkiye, where Table 5 reveals significant trailer idle time (23.95 min per cycle) in traditional systems and synchronization challenges in tube silage operations. Adapting Busato et al.'s methodology to Türkiye's farm size distribution and regional haul distances would provide a robust, data-driven DSS for domestic producers.

Future work should move from single-site observations to multi-region field datasets in Türkiye that quantify (i) total cost per ton (including film, labor, depreciation), (ii) dry matter loss and aerobic stability by storage type, and (iii) sensitivity to haul distance and utilization rate. A practical output would be a decision-support tool (farm scale, distance, machine access, fuel price, labor constraints) to recommend the economically robust silage system under Türkiye-specific constraints.

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