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Power requirements for corn silage harvesters and application of precision agricultural techniques: a review

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ABSTRACT

The energy requirements of corn silage harvesters and the application of precision agricultural techniques are essential for efficient and productive agricultural practices. The article aims to review previous studies on the energy requirements needed for different corn silage harvesting machines, and on the other hand, to present methods for measuring corn silage productivity directly in the field and monitoring it based on microcontrollers and artificial intelligence techniques. The process of making corn silage is done by cutting green fodder plants into small pieces, so special harvesters are used for this, called corn silage harvesters. The purpose of harvesting corn silage is to efficiently collect and store as many digestible nutrients as possible per unit of land area. The energy required to harvest corn silage is affected by many factors, including crop moisture, cutting lengths, particle size distribution, etc. This requires understanding the energy requirements of the harvesters used in the process. Using micro-sensors, the feed rate into corn silage harvesters is measured based on load cell data. This method helps in understanding the energy consumption and efficiency of the harvester during the feeding process, leading to more efficient and productive operations. On the other hand, artificial intelligence techniques are used to measure core size and cutting length to control machining parameters. We conclude from this review that precision agriculture techniques help farmers understand the efficiency of corn silage harvesters and know silage yield and quality, which helps them make informed decisions regarding energy use and thus obtain high productivity.

Keywords: agricultural practices, precision agriculture, artificial intelligence, energy requirements

INTRODUCTION

Green fodder plants are considered a very important fodder material for feeding animals. However, green fodder cannot be provided all year round. Silage is one way to keep forage plants green without drying them out, and provides permanently green fodder. Corn silage is a high-quality, productive, and inexpensive forage crop. Nutritious feed is obtained from corn silage in animal feed (Ergül, 2015; Kapustin et al., 2022).

The most important way to get a high yield from growing corn silage is to apply the correct agricultural techniques. It is necessary to know and apply all agricultural techniques from variety selection to the harvesting stage (Filya, 2001). Characteristics of Corn varieties grown for silage are the plant must be tall, the number of plant leaves and the percentage of leaves must be high, the ear weight must be good, the grains must be well fixed, the stem diameter that is detrimental to silage quality should not be too thick, and items must have a high protein value (Ergül, 2015; Abdul-Razak et al., 2016).

Chopping corn plants for use as fodder is essential in various aspects. Both dry and fresh green materials contain woody and hard parts. Chopping these solid parts makes it easier for animals to chew, swallow, and digest the solid parts of these materials (Demir and Çarman, 2008; Tawfeeq et al., 2018). However, the ability to digest does not always give a positive result by cutting the material. Dry matter cut or ground too short causes a type of intestinal disease (colic) in animals. Another advantage of the chopped material is the possibility of mixing it with other feed materials. This way, the food becomes more palatable. To make silage, green fodder plants must be cut into small pieces, so special machines are used for this. The machines used to do this on corn are called corn silage harvesters. Corn silage harvesters are self-propelled or tractor-pulled machines that shred forage crops to make silage by mowing in the field or picking up the previously mowed product from the field and blowing it onto a transport vehicle (farm vehicle, trailer, wagon, etc.). Corn silage is harvested when the grains have passed maturity and begun to harden, and the leaves are still green. During this period, the humidity of the plant reaches about 65-70% (Türkoğlu et al., 2010; Baktash and Alkazaali, 2016). The silage material must be cut to the optimum length of 10-50 mm to make proper silage (Pinar and Sessi, 1998). To obtain high work efficiency, the energy requirements of different corn silage equipment must be studied. Nieuwenhof (2003) studied the energy requirements of non-row-sensitive corn heads for a pull-type corn harvester. Lisowski et al. (2016) studied the effect of technical parameters on the energy required for the process of cutting, feeding, and picking material from corn plants. Zhang et al. (2003) evaluated the effect of processing roll configuration on energy consumption in corn silage harvesters. Özbek and Al-Sammarraie (2020) studied the energy requirements of a disc corn silage harvester when harvesting silage in a single row. To understand the energy consumption and efficiency of the harvesting machine during the harvesting process, precision agricultural techniques were used which led to more efficient and productive operations. Martel and Savoie (2000) evaluated sensors installed inside a silage harvester and the relationship between the observed signals and mass flow and moisture changes. Auernhammer et al. (1997) developed and field-tested productivity mapping on a self-propelled silage harvester. Rocha et al. (2022) developed a system for real-time quality assessment of cut corn silage using an image analysis algorithm to estimate kernel processing points based on a set of images. The article aims to review previous manuscripts on corn silage harvesters and the energy requirements needed for different corn silage harvesting machines based on the application of precision agricultural techniques.

CORN SILAGE HARVESTERS

To harvest corn silage, harvesters are used that operate according to different principles. Types of corn silage harvesters include:

Flail-type corn silage harvester

This type of silage machine harvests the material for silage by cutting it in the field with its freely rotating blades. The blades are arranged spirally around the shaft and do not come one after the other when their horizontal projection is captured. The free-rotating blades rotate opposite to the direction of the ground motion. The cut material is tilted in the direction of movement with the cover and cut with free blades. The shape and arrangement of the knives allow them to cut the plant and throw it away immediately. The circumferential speed of the blades ranges between 25-47 m/s. The number of blades depends on the working width. There are 16-22 knives with a working width of 1.10 m, and 26-30 free rotating blades with a working width of 1.30-1.50 m. The size of the chopping or chopping is changed by moving the counter blade closer to or farther from the active blades (Güner and Kafadar, 1998).

Disc corn silage harvester

In this type of silage harvester, the blades are connected to the disc at a radial or sub-radial angle to the axis of rotation. The number of knives with sharp, straight or curved edges ranges between 1-12. The number of disc revolutions is 540-1800 rpm. The average diameter of the disk is 1 meter. The circumferential speed of the blades changes from start to finish and ranges between 30-50 m/s. The blades on the disc ensure that the cut material is thrown through the output tube. Disc silage machines are used to cut green fodder and to make green fodder silage with the help of a shearing device added to the machine (Harmankaya, 2010; Belov, 2019).

Roller corn silage harvester

In this type of forage harvester, the material collection is similar to a disc corn silage machine. The difference between them is the arrangement of the pieces. The knives are installed on the circumference of the drum in the form of a helical curve under a certain angle (30 - 35°). The number of blades may vary depending on the circumference of the drum. The moving blades are tangential to the rotating drum in the plane of advancement and are positioned parallel to the axis of rotation. This structure makes it easy to sharpen the blades without disassembling them. One reason for the preference is that the speed is constant at every point of the blade length. The cylinder diameter is smaller than the disc diameter of a disc-type forage harvester, and its speed is almost double. As a result, a smaller size of the cut plant can be obtained. The cylinder speed is 1000-1500 rpm. The average diameter of the cylinder is 50-60 cm, and the average width is 40-60 cm. The smaller diameter of the cylinder, and therefore, its lower weight, means that the moment of inertia is small. This causes frequent blockages and requires additional engine power to overcome the excess torque. For this reason, 10-15% of spare engine power is needed in forage harvesters (Savoie et al., 2002; Tian et al., 2021).

Disc and roller silage harvesters can obtain the appropriate cutting size due to their structural characteristics. However, these machines are complex and expensive. On the other hand, the flail-type silage machine has universal use in terms of mowing and cutting grass and other silage materials, as well as being simple and inexpensive. However, these machines have the disadvantage that the cutting size is not suitable for silage, field losses are higher during harvesting of long-stem crops, and they have high energy requirements (Özbek and Al-Sammarraie, 2020). In all types of silage harvesters, the ideal design parameters of the blade (thickness, bend angle, sharpening angle), blade sharpness, blade type, number of blades, cutting unit diameter, blade circumferential speed, feed rate, and blade position should be determined to obtain the appropriate cutting size and ensure optimal energy consumption. In addition, factors such as type, thickness, height, humidity, maturity of the plant to be cut, and the angle of inclination of the plant also affect energy requirements (Zhang et al., 2003).

CORN SILAGE HARVESTER'S POWER REQUIREMENTS

In the experimental conditions, the maximum capacity of corn silage machines is 50 tons per hour for corn product cut at approximately 75% moisture and a cutting length of 12.7 mm. 60% of the value of this capacity can be used for cutting grass as a feed product. This result indicates that the 30-35 tons per hour theoretical capability of fodder silage machines as a fodder crop chopper was determined (Zeytinoğlu, 1998). Forage harvesters' power requirements are determined by the machine's operating conditions, the type of plants they collect, and the way the blades are arranged. The corn silage harvester's overall power requirements are made up of four parts:

1. The energy needed for the tractor to move itself
2. PTO power requirement for corn silage harvester
3. The force required to move the corn silage harvester
4. The energy required to pull the agricultural vehicle.

The energy required to move the tractor, farm wagon, and corn silage harvester can be calculated using known methods. Common calculation methods include measuring engine rotation, forward speed, and hourly fuel consumption (Kmiecik et al., 2023). The PTO power requirements of the combine can be determined by PTO torque meters. In research, 83-88% of the energy is allocated to cutting materials in disc-type harvesters, 5-8% of the energy is allocated to operating the collector, screw conveyor, and pre-pressure rollers, 5-6.5% is spent on the upper feed rollers, and 2-3.5% of it is consumed in the lower feed rollers. In roller-type harvesters, 75-85% of the total PTO energy is used in the shredding process, 4-7% in the feeder, 12-14% in the top feed, and 3-4% in the bottom feed. The energy required to cut material with the cylindrical type is, on average, 7% less than with the disc type. The coefficient of friction between steel and silage ranges between 0.2 and 0.8, depending on the type of silage, moisture content, cutter speed, and other factors. The friction angle between the polished steel surface and the silage can be taken as 0.49 for corn and alfalfa under conditions where the environmental velocity is 20-28 m/s (Güner and Kafadar, 1999; Al-Sammarraie et al., 2024). For corn silage, disc-type machines are typically utilized. These machines require 29.84–59.68 kW for a single row, 59.68–89.52 kW for a two-row, and more than 89.52 kW for a four-row tractor to operate effectively (Evrenosoğlu and Yalçin, 2006).

Bilgen and Sungur (1992) explained that the forward speed of the harvester affects energy consumption. When the forward speed increases, the energy consumption and the success of the field and product working capacity increase. While energy consumption in fields and products is reduced (Table 1).

Emen et al. (1996) also explained that the energy required is classified according to the way the corn silage harvesters move. Table 2 shows some of the operational features of flail-type harvesters. Table 3 shows some of the operational features of disc and roller harvesters.

PRECISION AGRICULTURE

Precision agriculture systems combine control, electronics, computers, databases, and calculation information. Components of precision agriculture technology include global positioning systems (GPS), geographic information systems (GIS), variable rate input application (VRA), and remote sensing (Vatandaş et al., 2005; Al-Sammarraie and Kırılmaz, 2023). Adapting and developing the right strategies and practices will ensure the success of precision agriculture (Earl et al., 2000). The sole goal in precision agriculture is not only to increase production but also to include practices that will allow savings in the use of inputs without causing a loss in yield (Al-Sammarraie and Jasim, 2021).

Table 1. Results obtained in silage corn yield (Bilgen and Sungur, 1992)

Forward speed (km/h)	Field working capacity (ha/h)	Product working capacity (t/h)	Power consumption (kW)	Field energy consumption (kWh/ha)	Product energy consumption (kWh/t)
2.70	0.125	6.20	27.8	222.4	4.48
3.64	0.168	8.36	36.2	215.5	4.33
4.75	0.219	10.91	45.6	208.2	4.18

Table 2. Some operational features of flail-type corn silage harvesters (Emen et al., 1996)

Features	Hanging type	Trailed type	Free rotating blade and cutting type
Working width (m)	1.1 – 1.3	1.3 – 1.5	1.8
Power requirement (kW)	>30	>40	>45
Loading capacity (t/h)	10 – 12	12 – 15	12
Economic year	8	8	8
Lifespan working area (ha)	500	500	500
Repair and maintenance expenses (% of purchase value per 100 ha)	20	20	20

Table 3. Some operational features of fixed blade (disc or roller) corn silage harvesters (Emen et al., 1996)

Features	Hanging type	Trailed type with rear connection	Silage trailer	Self propelled	Special corn silage machine
Power requirement (kW)	50	90	55	150	35 – 50
Work efficiency withering silage (t/h)	8	13	9	28	–
Economic year	10	10	8	10	8
Lifespan working area (ha)	750	800	500	1200	450 – 600
Repair and maintenance expenses (% of purchase value per 100 ha)	14	11	11	4	19 – 24

For understanding and explaining the geographical and physical variability of the land, several viewpoints are presented in crop production management. In order to put these insights into practice and achieve variable rate applications, a decision support system is needed. Furthermore, precision agriculture applications require technologies related to sensing, monitoring, control, and data transmission (Vatandaş et al., 2005; Al-Aani et al., 2018; Sharabiani et al., 2019). The power requirements, flow rate, and moisture content of silage harvesters can all be estimated by micro-sensor automation technology. Precise measurements of dry mass combined with field location yield productivity mapping that can be utilized for agricultural management. Simple, affordable, and precise sensors are required to track flow rate and humidity during the harvesting process. While microsensors are not widely available, the agricultural community and industry continue to show interest in them (Ali and Kaul, 2025). Moisture content can be determined by measuring electrical properties (Jones et al., 2022) or by absorbing infrared or microwave radiation (Auernhammer et al., 1995; Paul et al., 2000).

Savoie et al. (2002) used a 21.3 m^3 dump truck with four mass sensors installed underneath it, as shown in Figure 1. The weight of the harvested material is measured by the sensors, which then send the information to the data acquisition system to get the continuous cumulative weight.

Additionally, sensors to measure the moisture content and flow rate of silage in a forage harvester have been developed by researchers at the University of Wisconsin (Barnett and Shinners, 1998). Forage and hay equipment have a variety of sensor systems in place to measure mass flow (Shinners et al., 2003). Lee et al. (2005) also used load cells in silage harvesters to measure the mass of the empty and full silage cart before and after harvest to measure the mass of silage at each point in the field. The mass of the vehicle was continuously monitored using four load cells. On the four corners of the wagon silage box's bottom are load cells (Figure 2).

In order to understand and determine silage productivity at each point in the field, maps of variation in productivity are created. Depending on data obtained from precise measuring devices (weight sensors), it is possible to draw maps of variation in productivity. Maps are tools for processing formatted data and for analyzing and representing data. It also contributes to helping users make quick and reasonable decisions. In addition, the yield map can be a resource for precision agricultural applications in various fields. Producing high-resolution maps depends on collecting spatial data from enough geographically referenced points throughout practically the entire region. These processes require a lot of time and effort (Carrara et al., 2007). Mapping silage production is an important step to understand the extent of production variability and produce more animal feed with higher quality and better planning.

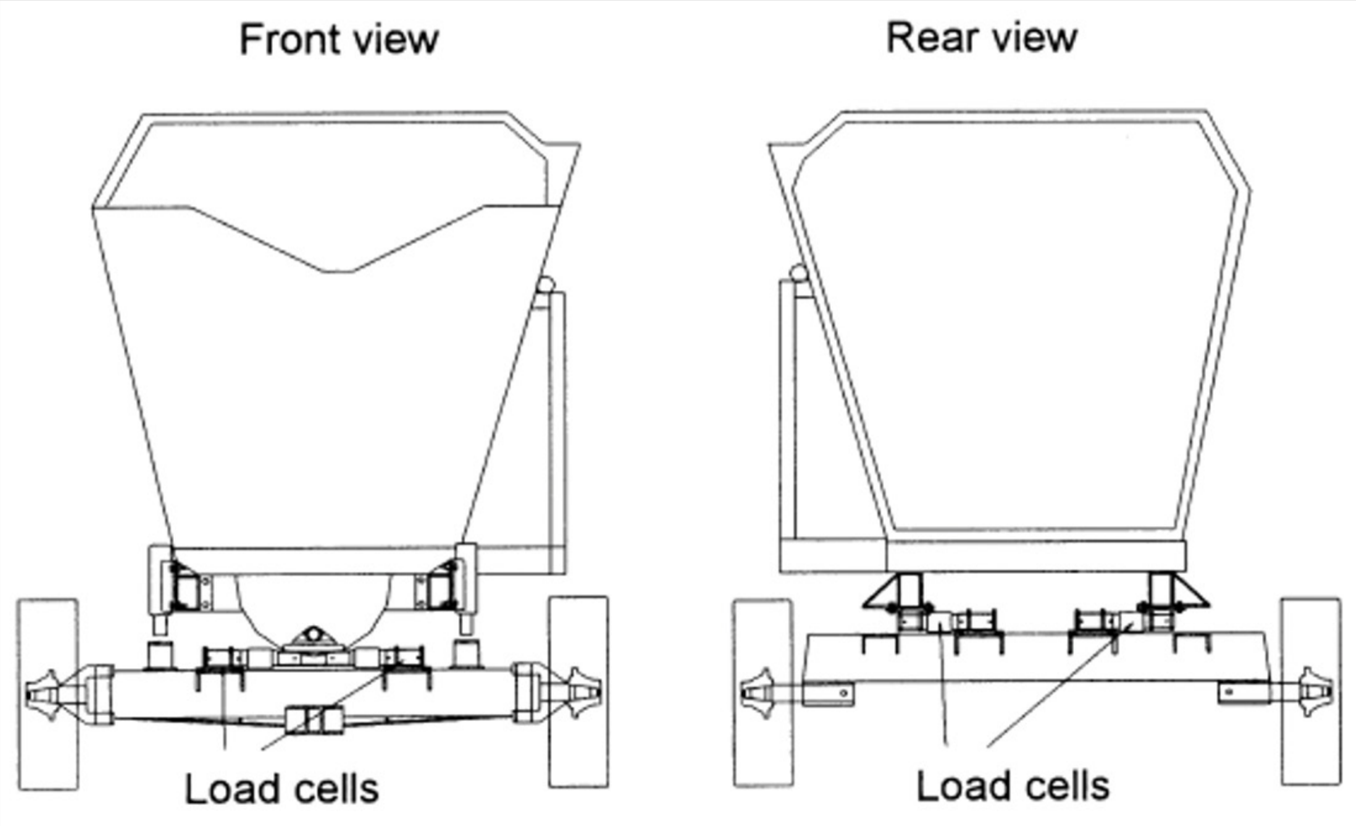

Figure 1. A schematic configuration of the unloading cart installed on four weight sensors

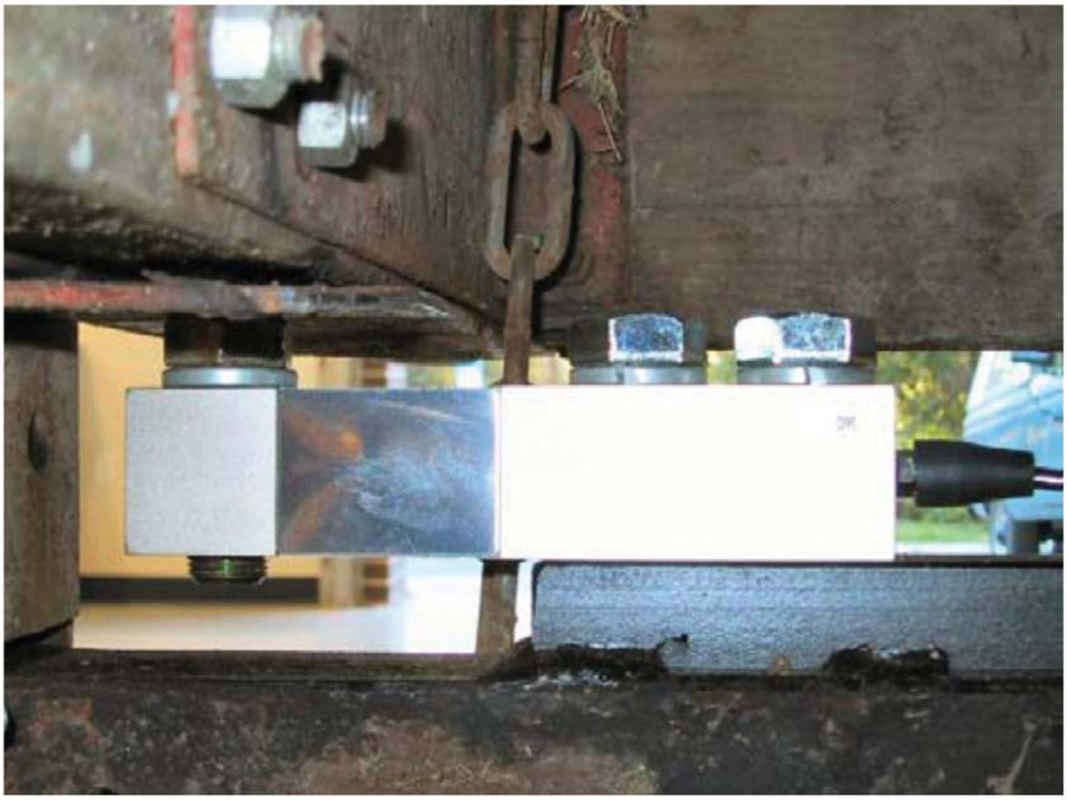

Figure 2. Load cell mounted on the four corners below the feed box of the vehicle

During the past fifteen years, a great deal of research has gone into yield mapping and yield monitoring for a variety of crops. The use of yield maps for grain harvesting has been extensively researched and implemented (Sirikun et al., 2021). And maps of variation in pH distribution in the soil (Al-Sammarraie et al., 2023). Also, draw a map of soil hardness to enhance the management of agricultural operations (Al-Aani and Sadoon, 2023). Additionally, using a high-sided trailer fitted with load cells and a differential GPS receiver, researchers at Silsoe College in the United Kingdom have developed a system for mapping the productivity of forages and root crops (Godwin and Wheeler, 1997; Godwin et al., 1999). The maps can visualize variation in corn silage yield, which suggests that site-specific crop management is required in the field (Figure 3) (Lee et al., 2005). Lee et al. (2002) also developed a fodder productivity mapping system using a DGPS system, load cells, Bluetooth modules for wireless data transmission, and a moisture sensor (Figure 4).

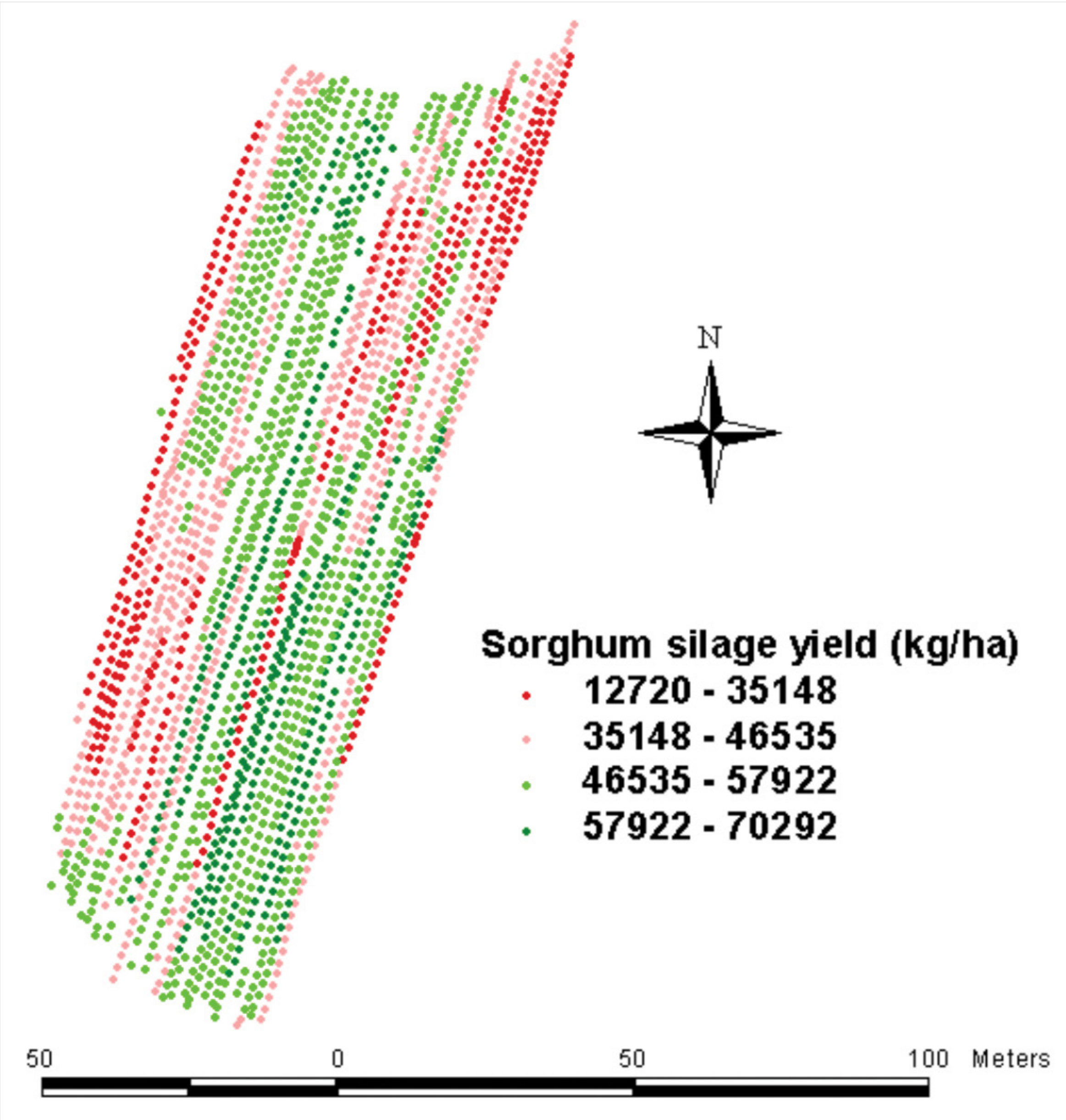

Figure 3. A map of the variation in maize silage yield

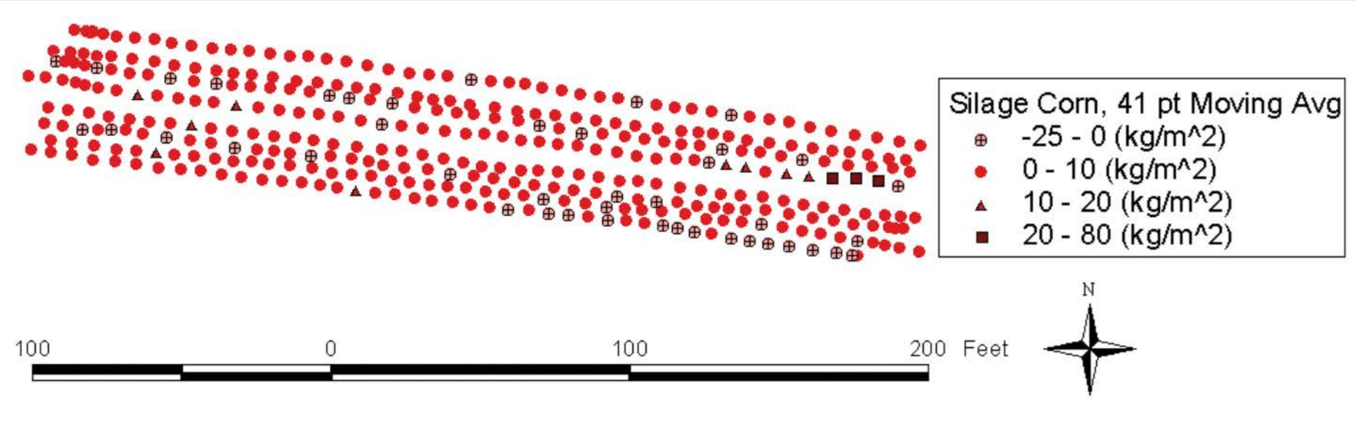

Figure 4. Distribution of silage productivity in the field

In addition to yield measurement and mapping techniques, plant plot size and corn grain size can also be measured using artificial intelligence technology (AI). AI plays a crucial role in sizing plant and grain plots by enabling efficient data collection, analysis, and forecasting in the agricultural sector. This technology can help farmers make informed decisions about their crops, leading to improved productivity and sustainability (Rocha et al., 2022; Gierz et al., 2024).

CORN SILAGE KERNEL PROCESSING

Assessing the processing of corn kernels is a crucial phase in ascertaining the caliber of silage obtained from a corn silage harvester (Johnson et al., 2003). Combinations with improper calibration can lose up to 25% of their quality (Marsh, 2013). In order to efficiently obtain the starch by minimizing the need for chewing while eating, the kernels must be sufficiently broken down. Two mill rolls crush and shear the plant to extract the kernel. In increments of 0.1 mm, the gap known as the processor gap (PG) typically ranges from 1 to 4 mm (Mertens, 2005). In corn silage threshing machines, a 3 mm clearance is thought to be optimal (Özbek and Al-Sammarraie, 2020). Using a particulate separator, the grower can measure the particle size by shaking three or four stacked trays, each with a predetermined sieve gap, to separate and weigh the sample (Rasmussen et al., 2021). If a more precise measurement is needed, laboratory measurements can also be carried out that involve shipping a sample of corn silage off-site for mechanical sieving. According to Mertens (2005), a screening system can be used by the farmer to determine the Corn Silage Processing Score (CSPS) of the kernels that have been separated from the stover, if only kernel fractionation is significant. Measuring particle lengths for silage fractions is frequently done to encourage physically effective neutral detergent fibers, which improve chew ability and maintain a healthy rumen pH (Mertens, 1997). Although it may be a laborious and time-consuming process to assess particle size, Convolutional neural networks (CNNs), a computer vision-based deep learning technique, can effectively evaluate the kernel processing of silage quality. Using a penny or other coin of known size, corn kernels are arranged in this manner on a dark background without coming into contact with any other specimens. Later in the system, the currency can be used to determine kernel sizes. After capturing an image, image processing is used to determine the boundaries of the nucleus particles. Next, each particle's maximum inscribed circle in pixels is determined, and this value is translated to the kernel particle size distribution in millimeters. A user can determine the processing quality of the kernel by looking at metrics like the average area or the percentage of particles smaller than 4.75 mm (Rasmussen and Moeslund, 2019). Previous studies have used computer vision techniques to estimate CSPS and quantify fragmentation levels (Drewry et al., 2019; Rasmussen and Moeslund, 2019; Luck et al., 2020; Rasmussen et al., 2021). Rasmussen et al. (2022) created

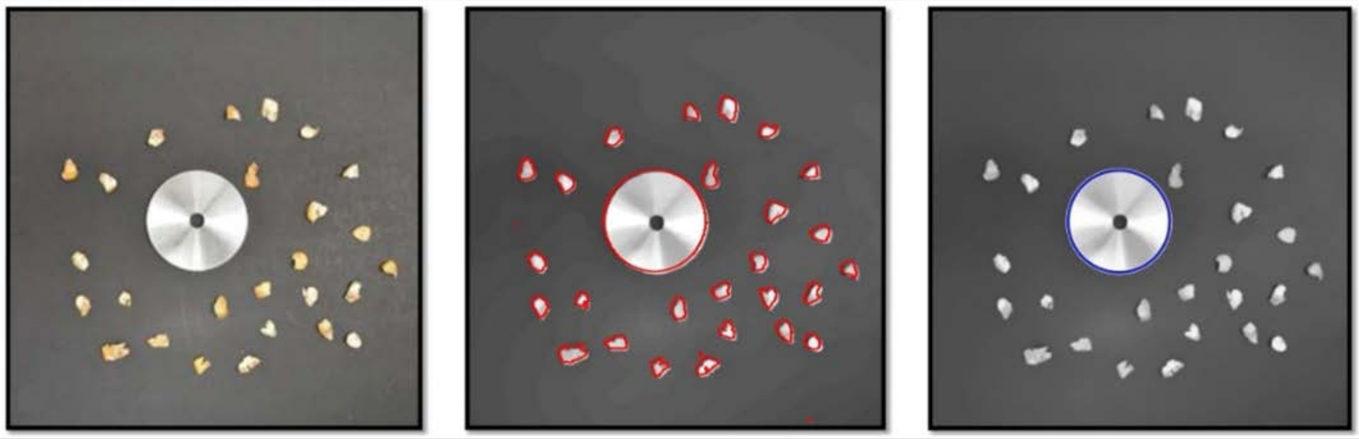

Figure 5. Kernel size analysis (the image is converted to grayscale, then the edges of the image are identified (in red), and the currency is identified and removed from the analysis (in blue)

an image dataset to segment kernels and trailing lengths in whole-plant corn silage. All parts are annotated, making it possible to estimate using an industry-standard like the CSPS. Given the conditions in the farmer's field, this would ideally enable the system to learn and estimate segmentation differences from images. Luck et al. (2019) used a smartphone, a plate, a coin, and a sheet of black construction paper to determine the degree of processing of the core. Pictures were taken of the nucleus with the coin, and using one of the developed phone applications, Silage SNAP, it filters the image to make the nucleus prominent and finds the coin in the center of the image to act as a scale, determining the size of each nucleus in the image (Figure 5). This method produces recordable data that can be used to gain insight into trends between fields and identify kernel processor maintenance and wear issues.

CONCLUSIONS

Corn silage production areas must be increased to fill the feed shortage and make clear the importance of silage to producers. Corn silage is a high-energy, flavorful feed that provides a greater amount of nutrients than grain obtained per unit area. Increasing the number of silage harvesters used in silage production and researching their applications will positively impact fodder production. There are different types of corn silage harvesters. Disc and roller silage harvesters have the advantage of getting the right cut size, however, these harvesters are complex and expensive. On the other hand, the flail-type silage harvester has the advantage of being simple and inexpensive. However, these harvesters have the disadvantage that the cutting size is not suitable for silage, the field losses are large, and they have high energy requirements. Precision agriculture using satellites and sensors to obtain data from the field has contributed to increasing the agricultural production of fodder by identifying and knowing productivity at every point in the field and drawing productivity maps. Maps are tools for processing formatted data and also for analyzing and representing data. It also contributes to helping users make quick and reasonable decisions. On the other hand, artificial intelligence technology, through convolutional neural networks, has contributed to measuring the size of the kernel and the length of the cut fibers, in monitoring the process of cutting and plucking the fodder and thus performing a correct calibration of the harvester to increase productivity and improve the quality of forage.

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