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Abstract

This structured critical review examines how structural, operational, and crop-related factors affect the energy performance of self-propelled forage harvesters. A documented literature search included journal articles, conference papers, technical reports, and DLG test reports. Power demand, specific energy, specific fuel consumption, throughput, and forage quality were compared. Particular attention is given to the theoretical length of cut (LOC) as a kinematic indicator linking feed velocity, cutterhead speed, and the number of active knives. The reviewed evidence shows that energy performance results from the combined effects of LOC, material throughput, crop properties, knife condition, roller-shredding intensity, header configuration, and engine-load control. Field-test data indicate that the reduction in specific fuel consumption with increasing LOC may reach a plateau rather than continue linearly. A conceptual framework is proposed to organize the interactions and trade-offs among energy demand, productivity, and

forage quality. The framework provides a basis for selecting variables in future experimental and predictive studies of forage-harvester performance.

Key words: energy performance; forage harvester; specific energy; structural parameters; theoretical length of cut.

Introduction

Modern self-propelled forage harvesters are high-performance machines designed to perform multiple technological operations in a single pass, including cutting of plant material, feeding, chopping to a predetermined theoretical length of cut (LOC), roller shredding, and transportation to accompanying transport units (Al-Sammarraie *et al*., 2025). This functional integration results in a high energy load of the process and imposes significant requirements for optimization of structural parameters and operating regimes.

Current product ranges from major manufacturers operating on the European market show considerable technical variation. Engine power extends from approximately 340 to 862 kW. Available cutterheads commonly have 20 to 40 knives, while maize headers range from about 6 to 10.5 m in working width. Depending on the configuration, the machines may also include multiple feed rollers, roller shredders, variable cutterhead arrangements, crop-flow sensors, and automatic load-control systems (CLAAS, n.d.; Fendt, n.d.; KRONE, n.d.). These differences should be considered when comparing machine energy performance.

An example of measured field performance is provided by the CLAAS JAGUAR 960 tested by DLG. The machine had an engine output of 480 kW and achieved a throughput of 209–236 t of fresh matter per hour, depending on LOC. It was equipped with a 9 m maize header, four pre-compression rollers, a 730 mm feed channel, and a 36-knife cutterhead (DLG TestService GmbH, 2023).

The forage harvesting process involves the sequential execution of several main operations, including feeding, chopping, optional roller shredding, acceleration, and discharge, as illustrated in Figure 1.

Figure 2 provides a more detailed view of the main working units and material flow in a self-propelled forage harvester. The crop is collected by the header and conveyed through the feed and pre-compression rollers to the cutterhead. During maize harvesting, the chopped material passes through the roller shredder before being discharged through the spout. The engine and drive system supply power to the main working units.

The energy performance indicators of forage harvesters, such as required power, specific fuel consumption ($L \cdot t^{-1}$ and $L \cdot ha^{-1}$), and specific energy ($kJ \cdot kg^{-1}$ or $kWh \cdot t^{-1}$), are directly related to the production cost of silage and the environmental footprint of forage production (Jokiniemi *et al*., 2021). At the same time, a significant variability exists in the reported results, which is mainly due to differences in testing conditions and in the definition of system boundaries, as some studies consider only field operations, while others also include transport activities.

In the literature, the energy characteristics of forage harvesters are evaluated using different groups of indicators, including power requirements, specific fuel consumption, and process-specific energy (Lisowski *et al*., 2016). The energy characteristics of the plant material chopping process have been the subject of numerous studies, demonstrating a strong dependence on both structural and technological parameters of the machine (Al-Sammarraie *et al*., 2025). It has been established that these indicators are also highly influenced by the physico-mechanical properties of the plant material, such as moisture content and structure, as well as by operating parameters (Savoie *et al*., 1989; Lisowski *et al*., 2019; Chen *et al*., 2023). From an engineering perspective, particular importance is attributed to the relationship between the structural parameters of the main working units -such as the diameter and rotational speed of the cutting drum, the number of knives, and the feeding rate- and the energy performance of the process (O'Dogherty, 1982; Chen *et al*., 2023). These parameters determine the cutting kinematics and the interaction between the knives and the material, which directly affects the energy required for fragmentation. The mechanics of cutting plant materials has been thoroughly analyzed by Persson (1987), while similar engineering principles have been discussed by Srivastava *et al.* (2006).

One of the most significant factors affecting energy consumption is the theoretical length of cut (LOC). Experimental studies have shown that increasing the length of cut leads to a reduction in the specific energy of the process (Savoie *et al*., 1989). This relationship has also been confirmed in recent standardized field tests, where a decrease in specific fuel consumption is observed with increasing LOC (DLG TestService GmbH, 2017; 2023).

An additional factor in maize harvesting is roller shredding, commonly referred to as kernel processing. It increases power demand. Its effect on forage quality and the selected LOC depends on the intended use of the silage, roller design, processing intensity, crop maturity, and ensiling conditions (Shinners *et al*., 2000; Johnson *et al*., 2003; Pintens *et al*., 2023). The technical condition of the cutting unit also has a significant impact on energy efficiency, as knife wear and sharpness can lead to increased fuel consumption and deterioration in chopping quality (Walther *et al.,* 2011).

Despite the substantial number of studies in this field, there is still a lack of an integrated approach that combines structural, kinematic, and energy parameters into a unified analytical framework (Al-Sammarraie *et al*., 2025). This limits the formulation of universal optimization criteria and restricts the direct comparability of results.

In this context, the present review paper aims to analyze the main structural parameters of forage harvesters and their influence on the energy performance of the harvesting and biomass processing process, as well as to systematize existing scientific findings in order to develop guidelines for improving energy efficiency.

Earlier studies usually examine separate relationships, such as the effect of LOC on energy demand, the power requirements of individual working units, or the estimation of crop flow (Savoie *et al*., 1989; Lisowski *et al*., 2019; Wang *et al*., 2023). The proposed framework brings these findings together in one structure. It links machine settings and crop properties with throughput, energy demand, and forage quality. LOC is used as a connecting variable rather than as the sole determinant of energy performance. The contribution of the framework is its structured basis for selecting variables and comparing future experiments. It does not introduce a new LOC equation and should not be interpreted as a validated predictive model.

Methodology

This study was designed as a structured critical review supported by a documented literature search. It addresses the following research question: Which structural, kinematic, operational, and crop-related factors influence the energy performance of self-propelled forage harvesters, and how can their interactions be incorporated into practical guidelines for machine optimization? The review covers literature published between 1980 and 2025 and focuses on power requirements, specific energy, specific fuel consumption, throughput, and the relationship between energy demand and the quality of the processed forage.

The literature search was conducted using Google Scholar and was supplemented by direct searches of journal and publisher websites and the DLG online test-report archive. Journal articles, conference papers, technical reports, and DLG test reports were considered. The main search terms included forage harvester energy consumption, forage harvester power requirement, theoretical length of cut, specific fuel consumption, crop feeding rate, knife number, roller shredder, kernel processor, and adaptive control. These terms were used separately and in different combinations. The reference lists of the selected publications were also screened to identify additional relevant studies. The records were first screened by title and abstract. Potentially relevant publications were then assessed in full text. Studies were included

when they directly addressed forage-harvester design, operating parameters, crop characteristics, energy requirements, fuel consumption, throughput, or forage quality. Publications concerning unrelated machinery or lacking sufficient technical information were excluded. Source quality was assessed from the clarity of the methods, operating conditions, and reported energy indicators.

The selection process resulted in 60 sources included in the final synthesis. These comprised scientific articles, conference papers, technical reports, standards, books, and manufacturer documentation. Sources were excluded when they concerned unrelated machinery, lacked sufficient technical information, or did not support the relationships examined in this review. The search and selection process was iterative, and exact counts of initially retrieved and excluded records were not retained. Because the study was designed as a structured critical review rather than a systematic review, a PRISMA flow diagram was not prepared.The selected studies were grouped according to structural, kinematic, operational, and crop-related factors. The crop-related findings were considered separately for maize, grass, and other forage crops. Reported values for power demand, specific energy, fuel consumption, and throughput were compared where the measurement conditions were sufficiently clear. Because the studies used different machines, crops, units, and system boundaries, the findings were analyzed through a critical narrative synthesis rather than a statistical meta-analysis. This synthesis was used to develop the proposed conceptual framework.

Energy performance indicators and evaluation methods

The management of the machinery fleet and the optimization of operating regimes are essential factors for reducing energy costs in agricultural production (Sharma *et al*., 2021), while the energy performance indicators of forage harvesters represent a key criterion for assessing the efficiency of the harvesting and biomass processing process. Similar relationships have been analyzed by Rotz and Muhtar (1992), who examined energy consumption across different forage harvesting technologies. These indicators reflect both the energy input of the machine and the efficiency with which this energy is utilized to perform the technological operation (Jokiniemi *et al*., 2021).

The energy evaluation of agricultural machinery and technological processes is a well-established field in agricultural engineering, where it has been shown that energy consumption is a function of both structural characteristics and operating conditions (Stout, 1990; Hunt, 2001).

In the scientific literature, several main groups of indicators are distinguished for assessing the energy efficiency of forage harvesters:

Power and load

The required power (P) (kW) is a fundamental parameter characterizing the energy demands of the process. It depends on cutting resistance, material feeding, and the operation of auxiliary systems such as the roller shredder and the discharge mechanism (Lisowski *et al*., 2019). The total power can be expressed in a generalized form as Equation (1):

$$P = P_{cut} + P_{feed} + P_{rs} + P_{loss}, \quad kW \qquad \text{(Eq. 1)}$$

where P_{cut} is the cutting power, P_{feed} is the feeding power, P_{rs} is the power required for roller shredding, and P_{loss} represents system losses.

Studies have shown that the share of energy required for cutting can constitute a significant portion of the total energy consumption; however, losses associated with material feeding and acceleration are also considerable (O'Dogherty, 1982; Lisowski *et al*., 2019).

Specific fuel consumption

One of the most commonly used practical indicators is specific fuel consumption, expressed as $L \cdot t^{-1}$ (liters per ton of fresh mass) and $L \cdot ha^{-1}$ (liters per hectare).

These indicators are widely applied in field tests and allow for a direct assessment of economic efficiency (DLG TestService GmbH, 2017; 2023).

According to review studies, typical values for self-propelled forage harvesters range from 0.48 to 0.87 $L \cdot t^{-1}$ under field conditions, and up to 3.0 $L \cdot t^{-1}$ when transportation is included (Jokiniemi *et al*., 2021).

Specific process energy

Specific energy (E_s) ($kJ \cdot kg^{-1}$ or $kWh \cdot t^{-1}$) is a fundamental engineering indicator that characterizes the amount of energy required to process a unit mass of material, as expressed in Equation (2).

$$E_s = \frac{P}{\dot{m}}, \quad kJ \cdot kg^{-1} \qquad \text{(Eq. 2)}$$

where P is the average power demand (kW), and $\dot{m}$ is the average mass flow rate ($kg \cdot s^{-1}$). Specific energy may also be expressed in $kWh \cdot t^{-1}$, where 1 $kWh \cdot t^{-1}$ corresponds to 3.6 $kJ \cdot kg^{-1}$.

This indicator enables direct comparison between different machines and operating regimes, regardless of productivity (Chen *et al*., 2023).

Experimental studies have reported specific energy values in the range of 30–40 kJ·kg^{-1} for the feeding and cutting processes, depending on the feeding rate and the rotational speed of the cutting drum (Chen *et al*., 2023).

Productivity and energy efficiency

Energy productivity can be expressed as the ratio between material throughput and power demand, as given in Equation (3):

$$E_e = \frac{q_m}{P},\ \mathrm{t \cdot kWh^{-1}} \qquad \text{(Eq. 3)}$$

Where E_e is the energy productivity (t·kWh^{-1}), q_m is the material throughput (t·h^{-1}), and P is the average power demand (kW).

Field tests have reported values in the range of 0.43–0.51 t·kWh^{-1}, depending on the LOC and machine configuration (DLG TestService GmbH, 2017; 2023). This indicator is particularly useful for comparing different machines and technological settings.

Methodological aspects and comparison challenges

A significant issue in the analysis of energy performance indicators is the lack of a standardized methodology for measurement and evaluation. Different studies adopt varying system boundaries and methods for determining mass flow rate and power (Jokiniemi *et al*., 2021).

In addition, parameters such as material moisture content, yield, crop type, and machine settings have a considerable influence on the results, which complicates direct comparison between individual studies (Al-Sammarraie *et al*., 2024; Al-Sammarraie *et al*., 2025).

Earlier work examined the relationship between power requirements and material flow in forage-harvesting equipment (Rotz and Muhtar, 1992). More recent studies use sensor data and component power measurements to estimate feeding rate in real time (Wang *et al*., 2023). The need for standardization of testing and evaluation methodologies is consistent with international approaches to the assessment of agricultural machinery (ASABE, 2011).

In summary, the energy performance indicators of forage harvesters represent a complex set of interrelated parameters that depend on both machine design and operating conditions. This necessitates an integrated approach to their analysis and highlights the need for systematizing the influence of structural factors on energy efficiency.

Structural parameters of forage harvesters and their influence on energy performance

The structural parameters of the main working units of forage harvesters play a key role in determining the energy performance of the harvesting and biomass processing process. These parameters define the kinematics of the interaction between the working elements and the material, as well as the mechanical loads generated during operation (O'Dogherty, 1982; Al-Sammarraie *et al*., 2025).

General principles of the design and operation of agricultural machinery indicate that both operational and energy performance are directly dependent on the combination of structural characteristics and operating conditions (Hunt, 2001). For the purposes of analysis, structural parameters can be grouped into three main categories: geometric, kinematic, and functional parameters.

Geometric parameters of the cutting unit

The main geometric parameters of the cutting drum include its diameter (D), number of knives (z), and cutting edge geometry. These parameters determine the cutting frequency and the conditions of material shearing.

The drum diameter influences the peripheral speed of the knives and the inertial characteristics of the system. A larger diameter results in a more stable cutting process but also increases inertial losses and power requirements (Al-Sammarraie *et al*., 2025).

The number of knives (z) is directly related to the cutting frequency and the theoretical length of cut (LOC). Increasing the number of knives leads to a reduction in particle length but also increases the number of cutting events and, consequently, the energy consumption (Savoie *et al*., 1989). Similar conclusions regarding the influence of knife condition on fuel consumption and operational efficiency have been reported by Wild *et al*. (2009), who emphasize the importance of an optimal maintenance strategy for the cutting unit. The geometry and sharpness of the knives also have a significant impact on the process. The influence of cutting edge geometry on the shearing process is consistent with general mechanical principles observed in cutting and tool–material interaction (O'Dogherty, 1982). A reduction in the cutting edge radius decreases the shearing force and, consequently, the energy consumption, whereas knife wear leads to increased fuel consumption (Walther *et al*., 2011). Crop properties also influence cutting resistance. Corn-stalk orientation affects the mechanical cutting response (Igathinathane *et al*., 2010). Tensile strength and tensile energy also vary with stalk position, variety, and moisture content (Zhang *et al*., 2016). These differences can cause load variation even when the machine settings remain unchanged. Knife condition should be treated as a measured

operating variable rather than as a fixed machine characteristic. Sharpening interval, knife–shearbar clearance, power demand, and fuel consumption should be recorded during field tests. These data should be evaluated together with crop moisture and material throughput to separate the effect of knife wear from changes in machine load (Wild *et al*., 2009; Walther *et al*., 2011).

Kinematic parameters

Kinematic parameters include the rotational speed of the cutting drum (n) and the linear material feed velocity (v_{feed}). These parameters determine the dynamics of the process and the interaction between the knives and the plant material.

The rotational speed of the drum directly affects the cutting speed and the frequency of interaction between the knives and the material. Increasing the rotational speed enhances productivity but also leads to higher energy consumption due to increased dynamic loads. The feeding rate (v_{feed}) determines the mass flow rate of the material and has a significant influence on the load of the cutting unit. Studies have shown that there exists an optimal range of feeding rate at which minimum specific energy is achieved while maintaining high chopping quality (Chen *et al*., 2023).

The interaction between (n), (z), and (v_{feed}) determines the theoretical length of cut (LOC), which can be expressed as a function of these parameters.

Functional parameters and auxiliary systems

The roller shredder consists of two counter-rotating rollers that crush and shear the material. Its main parameters are the roller gap and speed differential. The additional power demand and the resulting material quality depend on roller gap, speed differential, crop maturity, target LOC, and the intended use of the silage (Shinners *et al*., 2000). Feeding mechanisms also play an important role by ensuring uniform material flow to the cutting unit. Irregular feeding leads to peak loads and increased energy losses (Lisowski *et al*., 2019).

Interaction between parameters and energy performance

Structural and kinematic parameters do not act independently but form a complex system of interrelated factors. For example:

- an increase in (z) → a decrease in LOC → an increase in specific energy
- an increase in (n) → higher productivity → increased power demand
- an increase in (v_{feed}) → higher throughput → risk of overloading

Experimental and field studies have shown that the optimization of these parameters can lead to a significant reduction in energy consumption while maintaining or improving product quality (DLG TestService GmbH, 2017; 2023). Similar relationships between structural parameters and energy performance have also been identified by Lisowski *et al*. (2016), who demonstrated the substantial influence of the number of knives, rotational speed, and feeding rate on the required cutting power.

Component-level studies provide supporting evidence for the effect of cutting-unit design. Bochat and Zastempowski (2020) showed that drum configuration affected cutting effectiveness and energy demand during rape-straw cutting. Wang et al. (2018) found that the structural and operating parameters of a straw-chopping device affected chopping quality and power consumption. These studies concern different materials and machine configurations. Their quantitative results cannot be transferred directly to self-propelled forage harvesters and are used only as qualitative engineering evidence.

Theoretical length of cut as an integral parameter

The theoretical length of cut (LOC) represents one of the key parameters in the analysis of biomass fragmentation processes and has an inherently integral character. It is not an independent parameter but is determined by the combined effect of the structural and kinematic characteristics of the machine.

For a cutterhead equipped with (z) active knives, the theoretical length of cut can be expressed by the basic kinematic relationship (eq. 4) (Persson, 1987; Savoie *et al*., 1989):

$$LOC = \frac{60000 \cdot v_{feed}}{z.n} \quad \text{(Eq. 4)}$$

where LOC is the theoretical length of cut (mm),v_{feed} is the linear velocity of the material entering the cutterhead ($m \cdot s^{-1}$), z is the number of active knives passing the shearbar during one drum revolution, and n is the cutterhead rotational speed (min^{-1}).

The equation shows that LOC increases with feed velocity and decreases with knife number and cutterhead speed. LOC is a kinematic set-point and not a direct measure of the actual particle-size distribution. Feed compression, slippage, crop properties, and recutting may cause the actual particle size to differ from the theoretical value. This distinction is important when interpreting field results. Image analysis of chopped alfalfa and maize showed that sieve-based methods underestimated the actual particle length by an average of 31% (Savoie *et al*., 2014). Therefore, theoretical LOC should be treated as a machine setting, while the resulting material should be described by its particle-size distribution. Actual particle-size distribution can be

assessed by screening according to ANSI/ASAE S424.1 (ASABE, 2012). Computer-vision methods provide an alternative for estimating particle-size distributions without conventional sieving (Igathinathane *et al*., 2009). This distinction is relevant because particle size influences the physical effectiveness of forage fibre and, consequently, feed quality (Mertens, 1997). The relationship between LOC and forage quality was also examined by Johnson *et al.* (2003). The authors compared several theoretical cut lengths with and without mechanical processing. Both factors affected particle-size distribution and forage digestibility. For a given length of material, a larger LOC corresponds to fewer theoretical cutting events per unit length. It does not necessarily mean fewer knife passes per unit time, as the knife-pass frequency is determined by zn/60. Under the tested conditions, a longer LOC was generally associated with lower specific energy and fuel consumption (Savoie *et al*., 1989; DLG TestService GmbH, 2017; 2023).
However, LOC also affects particle-size distribution and the physical structure of the processed forage. In maize silage, a longer LOC can be combined with roller shredding to maintain kernel fragmentation and forage quality. This additional processing increases power demand (Shinners *et al*., 2000). Therefore, LOC should not be optimized only for minimum energy consumption. Crop moisture, target particle size, and roller-shredder settings should also be considered.

Influence of structural parameters on energy efficiency

Modern approaches for the analysis and prediction of energy performance in forage harvesters include the application of machine learning methods, which enable the estimation of required power as a function of operating parameters (Wang *et al*., 2023; Al-Sammarraie *et al*., 2024). The influence of structural parameters on the energy performance of forage harvesters represents a complex process in which individual factors interact and mutually influence each other. Existing studies indicate that it is not a single parameter, but rather their combination that determines the overall energy efficiency of the machine (Al-Sammarraie *et al.,* 2025).
It has been established that the selection of the operating regime during maize silage harvesting has a significant impact on energy consumption and operational productivity of forage harvesters (Kmiecik *et al*., 2023). Earlier experiments showed that cutting velocity affects the power required for maize-stalk chopping (Wu *et al*., 2001).
Zhang *et al*. (2019) examined the bending and crushing behaviour of corn straw through simulation and laboratory tests. The results help explain material deformation during chopping, but they do not provide whole-machine power or fuel-consumption data for self-propelled forage harvesters.

The design of the crushing and discharge system also affects material processing. Niu *et al.* (2021) showed that cutter-shaft speed and blade configuration influenced the crushing quality of silage corn. These parameters should therefore be considered together with LOC and material throughput.

Influence of theoretical LOC

LOC affects cutting frequency and machine load, but its effect on specific fuel consumption is not always linear.

Figure 3 presents individual observations of theoretical length of cut and specific fuel consumption from two DLG field tests (DLG TestService GmbH, 2017; 2023). The data points are not connected because the cited tests did not include measurements at intermediate LOC values.

For the CLAAS Jaguar 960, specific fuel consumption decreased from 0.53 $L \cdot t^{-1}$ at 4 mm LOC to 0.47 $L \cdot t^{-1}$ at 7 mm and remained unchanged at 12 mm. This result indicates a plateau rather than a continuous reduction with increasing LOC. Field tests conducted by Marsh (2013) also showed that reducing the cut length from 17 to 11 mm substantially decreased fuel-use efficiency and harvesting capacity. This confirms that the effect of LOC should be evaluated together with machine throughput. As shown in Figure 4, LOC links cutterhead kinematics with the process response, while crop, operating, and machine-related factors also influence energy performance and forage quality.

Influence of the number of knives and rotational speed

The number of knives and the cutterhead rotational speed determine the frequency of knife passages. Increasing either parameter generally produces finer chopped material but also raises the cutting and dynamic power demand. Chen *et al*. (2023) reported an increase in power demand at higher cutterhead speeds under the examined conditions. Knife–shearbar clearance also affects cutting resistance. Excessive clearance increases material deformation and may increase energy demand (Al-Sammarraie and Özbek, 2019). These parameters should therefore be adjusted together with feed velocity, material throughput, and the target LOC.

Influence of the feeding rate

The linear feed velocity (v_{feed}) influences material throughput and the load of the cutting unit. At low values, the machine operates inefficiently and specific energy increases. At high values, productivity increases, but the risk of overloading also rises.

An optimal feeding range allows minimization of energy consumption while maintaining efficient operation (Chen *et al*., 2023; Wang *et al*., 2023).

Influence of the roller shredder

The intensity of roller shredding is determined mainly by the peripheral speed differential and the gap between the rollers. Commercial systems may operate with speed differentials of 30%, 40%, or 50% (KRONE, n.d.). A higher differential increases the shearing action and improves kernel fragmentation. However, it may also increase the power required for processing. A smaller roller gap increases compression and improves kernel breakage, but it also increases material resistance. A wider gap reduces the processing load but may leave more kernels insufficiently fragmented. The settings should therefore be selected according to crop maturity, moisture content, LOC, and the intended use of the silage (Shinners et al., 2000; Johnson et al., 2003).

When both rollers operate at the same peripheral speed, the unit acts mainly as a crumpler.

During maize harvesting, roller shredding increases power demand and improves kernel fragmentation. However, the selection of LOC and processing intensity depends on the required forage quality and ensiling conditions (Shinners et al., 2000; Johnson et al., 2003). Kernel fragmentation in maize silage is commonly evaluated using the kernel processing score (KPS). Image analysis can also be used for its assessment (Drewry *et al*., 2019; Rocha *et al*., 2022). Image-based estimates of KPS were also correlated with in situ dry matter disappearance. This supports their use for rapid assessment of feed quality during harvesting (Luck *et al*., 2020). Experimental shredding systems have shown that processing intensity affects both energy demand and particle characteristics. Zhang *et al*. (2003) reported a specific shredding energy of 2.5-5.9 $kWh \cdot Mg^{-1}$ DM, depending on the roller configuration and crop conditions. More recent work showed that impact-shredding caused greater disruption of the fibre and kernel fractions than conventional roller shredding (Pintens *et al*., 2023). Recent studies have examined alternative grain-crushing units for silage maize harvesters. These include disc-type devices and screw-notched crushing rollers (Mou *et al*., 2020; Geng *et al*., 2021). The results show that the design of the crushing unit affects processing performance.

Influence of crop and machine conditions

Energy performance cannot be explained by LOC alone. Crop-specific quality requirements also affect the selection of chopping settings. Wan *et al*. (2021) combined cattle-feeding trials with chopping-device tests for forage rape and determined operating parameters for different

crop stages. This supports evaluating LOC together with crop maturity and feeding quality. Crop type, moisture content, yield, and material structure affect cutting resistance, throughput, and load variability (Lisowski *et al*., 2019; Jokiniemi *et al*., 2021). Header configuration, engine-load control, knife condition, and the discharge system also influence total power demand and fuel consumption (Rotz and Muhtar, 1992; Walther *et al*., 2011; Al-Sammarraie *et al*., 2025). Therefore, machines operating at the same LOC may have different specific energy and fuel-consumption values. Header design can also contribute substantially to power demand. In field tests of a prototype non-row-sensitive corn header, Nieuwenhof (2003) reported approximately twice the power demand of a conventional header of the same width, mainly because of higher no-load power.

Crop-specific and cutterhead considerations

Crop type changes both the machine configuration and the relevant quality criteria. In maize, chopping is commonly combined with roller shredding, and LOC must be considered together with kernel fragmentation and shredder settings (Shinners *et al*., 2000; Johnson *et al*., 2003; DLG TestService GmbH, 2023). In grass harvesting, a roller shredder is normally not used. Energy demand is influenced mainly by crop moisture, swath density, feed uniformity, and throughput (Savoie *et al*., 2002; Jokiniemi *et al*., 2021). For forage rape and other crops, crop maturity and material properties require separate operating settings (Wan *et al*., 2021). Results obtained for maize therefore cannot be transferred directly to grass or other forage crops.

Cutterhead design may also affect energy demand and particle formation. The DLG test compared V-Max and V-Flex drums, each equipped with 36 knives, and found differences in particle-size distribution (DLG TestService GmbH, 2023). However, many of the reviewed studies did not report whether the drum was open or closed or whether the knives had a V-shaped or spiral arrangement. The available data are therefore insufficient for a quantitative comparison of these designs. Future studies should report these configurations explicitly.

Summary of influences

Table 1 summarizes the effects of the main structural, operational, and crop-related factors. LOC shows a consistent relationship with specific energy consumption, but the magnitude of this effect depends on crop properties and operating conditions. Knife number, cutterhead speed, feed velocity, material throughput, knife condition, roller-shredding intensity, and engine-load control act together. Energy optimization therefore requires a multifactor assessment rather than adjustment of LOC alone.

Conceptual framework of parameter interactions

Figure 4 summarizes the proposed framework. Knife number, cutterhead speed, and feed velocity determine the theoretical LOC. Crop properties, material throughput, knife condition, and roller-shredder settings modify the resulting process response. Energy performance and forage quality are therefore evaluated together.

The framework can be used to select variables for experimental studies, compare results obtained under different operating conditions, and define inputs for future predictive models. Its application requires the simultaneous measurement of machine settings, crop properties, material throughput, power demand, fuel consumption, and particle quality. These variables should be recorded during the same test runs and expressed in comparable units. This would allow the interactions between factors to be quantified.

The framework has several limitations. It was developed from studies using different machines, crops, measurement methods, and system boundaries. The proposed relationships have not been tested within a single experimental design, and their relative effects cannot be quantified from the available evidence. Interactions among LOC, throughput, crop moisture, knife condition, and roller-shredder settings may also vary under different field conditions. The framework should therefore be used to organize variables and research hypotheses, rather than to predict power or fuel consumption. Experimental validation is required before quantitative optimization rules can be proposed.

Comparative analysis of results from different studies

To provide a clearer understanding of the influence of structural and technological parameters on energy performance, a comparative analysis of results from various experimental and review studies has been conducted.

Available data indicate significant variability in energy performance values (Table 2), which is due to differences in operating conditions as well as in the measurement methodologies used. Nevertheless, common trends can be identified.

Analysis of result comparability

Across the reviewed studies, a longer LOC was generally associated with lower energy demand. However, the magnitude and pattern of this relationship varied between machines and operating conditions. At the same time, significant differences are observed in the absolute values of the indicators. These differences are mainly due to:

- different system boundaries (field operation only vs. field + transport) (Jokiniemi *et al.*, 2021),
- variations in crop type and material moisture content (Lisowski *et al*., 2019),
- differences in machine design configurations (DLG TestService GmbH, 2017; 2023).

It is particularly important to note that results from laboratory or test bench studies (Chen *et al*., 2023) cannot be directly compared with field experiments, as they typically consider only individual machine components.

A formal meta-analysis was not performed because the reviewed studies use different system boundaries and report energy performance in different units, including $kJ \cdot kg^{-1}$, $kWh \cdot t^{-1}$, $L \cdot t^{-1}$, and $L \cdot ha^{-1}$. Many studies also do not provide the sample size, variance, or a comparable reference treatment required to calculate standardized effect estimates. Combining these results statistically could therefore produce misleading conclusions. The available quantitative values and common trends are instead summarized in Table 2 and Figure 3.

Modern technologies and trends for energy efficiency optimization

The modern development of forage harvesters is focused on improving energy efficiency through the implementation of intelligent control systems, sensor technologies, and real-time optimization of operating regimes. These approaches enable adaptation of the machine to changing working conditions and minimization of energy losses (Al-Sammarraie *et al*., 2025).

Automatic load control systems

One of the main trends is the use of automatic engine load control systems, which regulate rotational speed and feeding rate depending on current operating conditions. These systems allow the machine to maintain an optimal operating regime and reduce fuel consumption.

Fuel consumption depends on engine load and operating regime (Grisso *et al*., 2004). Field studies of self-propelled forage harvesters also show that operating parameters influence fuel use and productivity (Krzyżaniak *et al*., 2023).

Sensor systems and process monitoring

Advances in sensor technologies enable real-time measurement of parameters such as material mass flow rate, engine load, moisture content of plant material, and chopping quality.

Based on these data, models for process optimization can be developed. Studies have shown that the use of indirect methods for estimating material flow rate through the measurement of

power in individual machine units allows for more accurate evaluation of energy performance (Kmiecik *et al*., 2023).

Earlier sensor studies showed that material flow can be estimated from feed-roll displacement, crop impact force, and cutterhead torque (Martel and Savoie, 2000; Savoie *et al*., 2002). Moisture correction improved the accuracy of torque-based estimates. These measurements provide useful data for throughput monitoring and machine-load control.

Optimization of operating regimes

Modern approaches include the optimization of parameters such as feeding rate, drum rotational speed, and theoretical length of cut (LOC), depending on operating conditions. This enables the achievement of an optimal balance between productivity, quality, and energy consumption.

Studies have demonstrated that dynamic adjustment of these parameters can lead to a significant reduction in the specific energy of the process (Chen *et al*., 2023).

Structural innovations

Modern structural innovations in agricultural machinery are aimed at improving functional efficiency, reliability, and adaptability to specific working conditions (Hunt, 2001).

Manufacturers implement various design solutions to enhance performance, including optimized knife geometry, improved feeding systems, efficient roller shredding systems, and reduction of mechanical losses.

These innovations lead to better energy utilization and reduced fuel consumption.

Future perspectives

Recent studies show a shift from fixed machine settings to sensor-based monitoring and data-driven control. Wang *et al*. (2023) estimated crop feeding rate from speed, torque, and power data. This information can support real-time machine-load control. Al-Sammarraie *et al*. (2024) used machine-learning models to predict PTO power demand, while Rocha *et al*. (2022) applied image analysis and machine learning to assess the kernel processing score. These approaches can support adaptive machine adjustment, although their direct effect on fuel consumption still requires field validation.

Deep-learning methods have also been used to identify kernel fragments in non-separated maize silage images (Rasmussen and Moeslund, 2019). A later study extended this approach to the detection of both kernel fragments and oversized stover particles in harvested maize silage images (Rasmussen and Moeslund, 2021). This allows kernel fragmentation and particle

overlength to be evaluated simultaneously. Later work showed that image annotation remains an important limitation when training such models (Rasmussen *et al*., 2022). Machine vision has also been applied to control material delivery from a silage harvester to a transport vehicle. You *et al*. (2024) developed a system for detecting the position of the trailer and controlling the discharge spout. Detection accuracy exceeded 90% under the tested conditions, although the system focused on material delivery rather than energy optimization.

Dai *et al*. (2025) studied an integrated machine for silage crushing, shredding, and baling. Blade number, length, and angle affected productivity and shredding quality. The machine and its operating process differ from those of a self-propelled forage harvester. Its results cannot be used to estimate forage-harvester energy demand and are cited only as qualitative evidence that blade configuration affects the performance of silage-processing equipment.

Commercial systems show how sensor data can be used in forage harvesting (Al-Sammarraie *et al*., 2025). HarvestLab 3000 and NutriSense NIR measure crop moisture and composition during harvesting (John Deere, n.d.; New Holland Agriculture, 2021). These data can support decisions on LOC and roller-shredder settings, but the sensors do not measure energy consumption directly. CEMOS AUTO PERFORMANCE adjusts engine output and ground speed according to crop throughput (CLAAS, n.d.). CLAAS reports potential fuel savings of up to 12% under suitable conditions. This manufacturer-reported value should not be interpreted as a general result for all crops and operating conditions.

Conclusions

This review examined the structural, operational, and crop-related factors affecting the energy performance of self-propelled forage harvesters. The main conclusions are:

1. Energy performance results from the combined effects of structural, kinematic, operational, and crop-related factors. LOC is a useful kinematic indicator, but it is not the sole determinant of energy efficiency.
2. A longer LOC is generally associated with lower specific energy and fuel consumption. The magnitude of this effect depends on the machine, crop, and operating conditions and may reach a plateau. LOC also affects particle-size distribution and forage quality.
3. Knife number, cutterhead speed, linear feed velocity, material throughput, crop properties, knife condition, roller-shredder settings, header configuration, and engine-load control should be evaluated together.

4. Sensor technologies and adaptive control systems can support real-time adjustment of machine settings. Their effect on fuel consumption and forage quality still requires wider field validation.
5. The proposed framework provides a structured basis for selecting variables in future experiments and predictive models, but it remains conceptual. Validation should measure machine settings, crop properties, throughput, power demand, fuel consumption, and particle quality during the same test runs. The resulting data could support predictive models of forage-harvester performance and energy efficiency.

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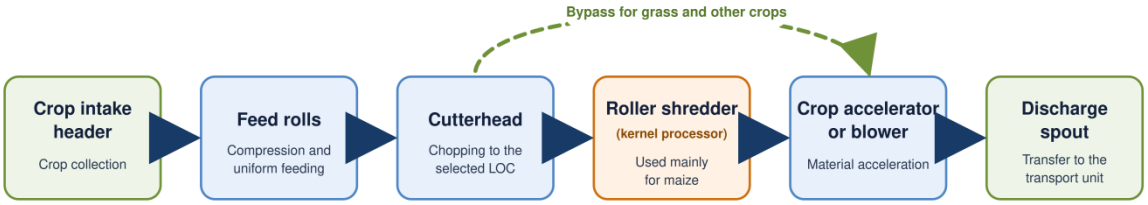

Figure 1. Simplified crop-flow path in a self-propelled forage harvester. The roller shredder is used mainly for maize and is bypassed for grass and other crops. Authors' schematic based on Shinners *et al*. (2000) and DLG TestService GmbH (2023).

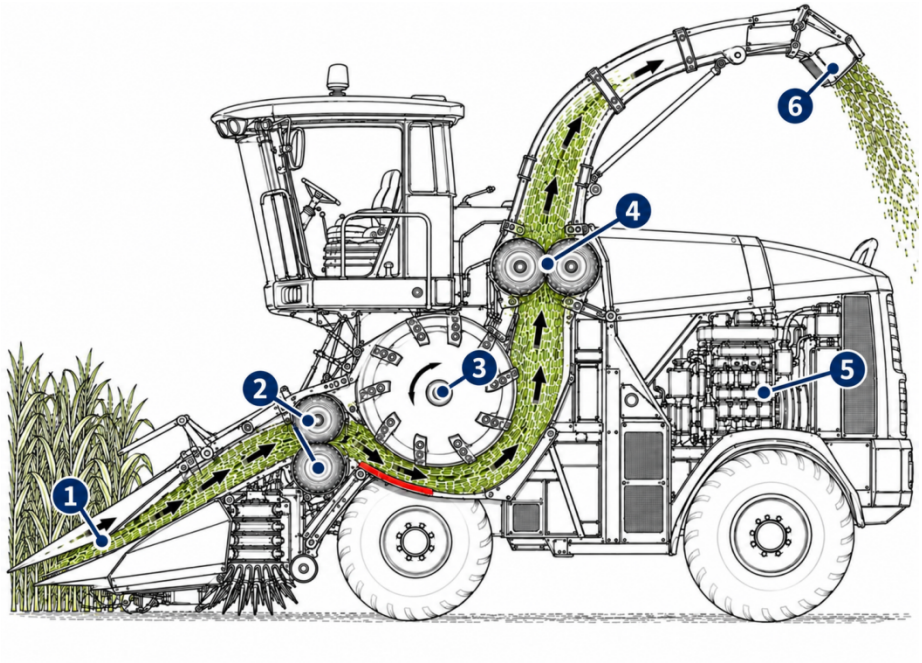

Figure 2. Technological diagram of the main working units and material flow in a self-propelled forage harvester: 1, maize header; 2, feed and pre-compression rollers; 3, cutterhead; 4, roller shredder; 5, engine and drive system; 6, discharge spout.

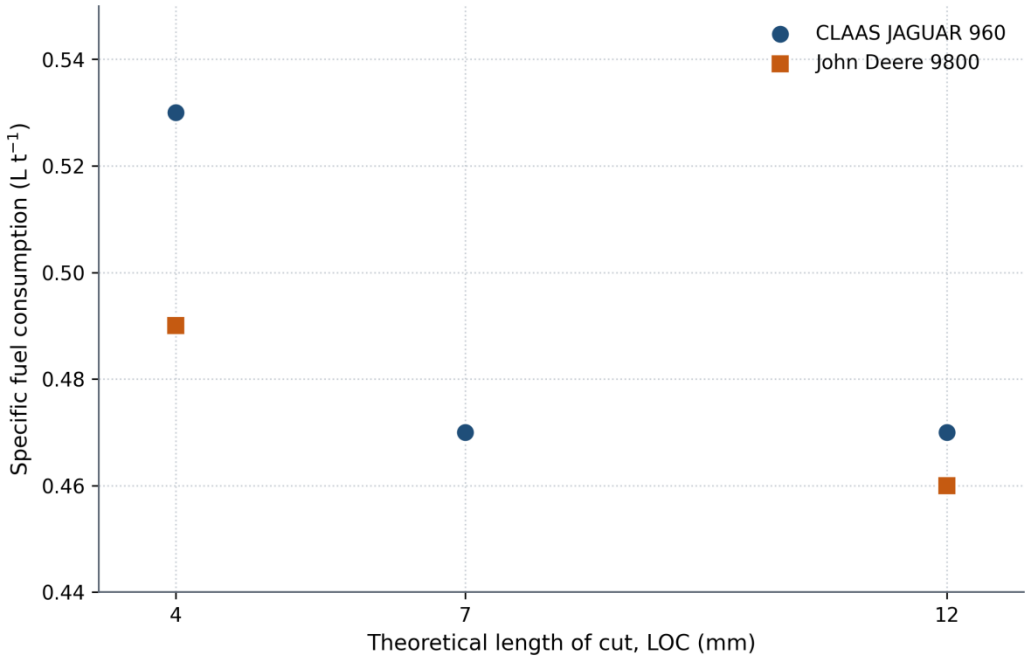

Figure 3. Relationship between theoretical length of cut and specific fuel consumption of two self-propelled forage harvesters, based on individual observations reported by DLG TestService GmbH (2017, 2023).

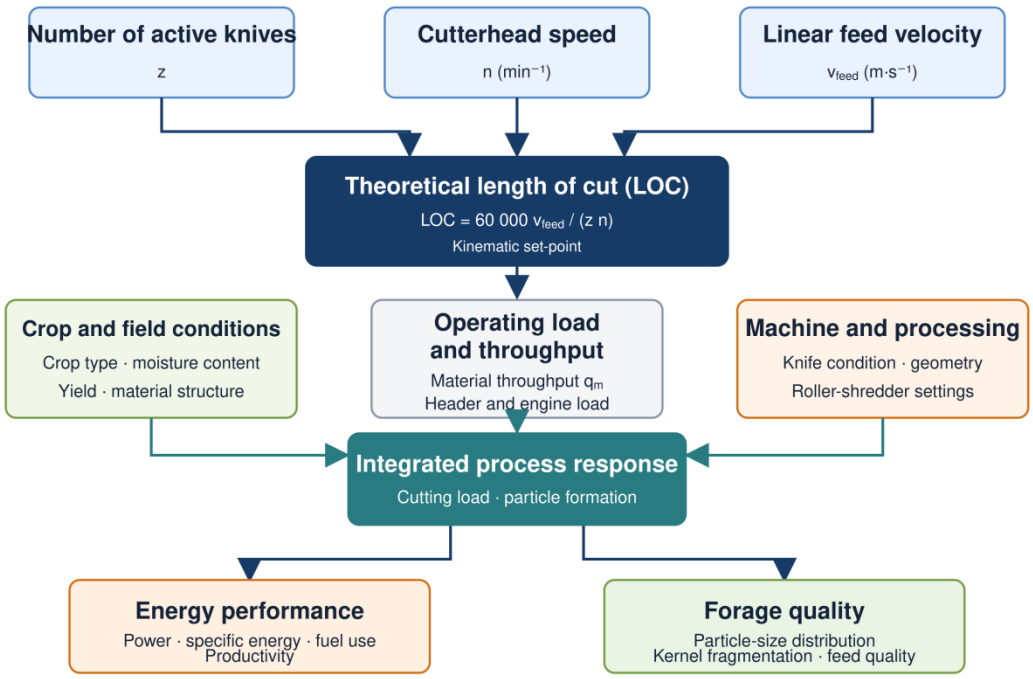

Figure 4. Conceptual framework linking theoretical length of cut with crop, operating, and machine-related factors affecting forage-harvester energy performance and forage quality.

Table 1. Influence of key parameters on the energy efficiency of forage harvesters

Parameter	Effect on energy	Comment
LOC ↑	Specific energy generally ↓	Effect depends on crop and operating conditions
Number of knives z ↑	Energy ↑	Finer chopping
Cutterhead speed n ↑	Energy ↑	Higher cutting frequency and dynamic losses
Linear feed velocity v_{feed} ↑	Energy ↓ / ↑	Optimum range and overload risk
Crop moisture and properties	Variable	Changes cutting resistance and particle formation
Material throughput q_m ↑	Specific energy ↓ / ↑	Depends on machine loading
Knife wear ↑	Energy and fuel use ↑	Maintenance-related effect
Roller-shredding intensity ↑	Energy ↑	Improved kernel fragmentation
Header and engine-load control	Variable	Machine- and condition-dependent

Table 2. Comparison of energy performance indicators across different studies

Author	Object of study	Key parameters	Energy indicators	Main findings
Savoie *et al*. (1989)	Cutting process	LOC, moisture	↓ Energy with ↑ LOC (~22%)	LOC is a key factor
O'Dogherty (1982)	Cutting theory	Knife geometry	Dependence on angle and speed	Mechanics of cutting
Lisowski *et al*. (2019)	Working units	Moisture, PSD	Significant energy variation	Energy ≠ cutting only
Jokiniemi *et al.* (2021)	Review (field data)	Yield, system	0.48–0.87 L·t^{-1}	High variability
Chen *et al*. (2023)	Feeding-cutting mechanism	v_{feed}, n	~37.6 kJ·kg^{-1}	Parameter optimization
Shinners *et al.* (2000)	Roller shredder	LOC + processing	Energy–quality balance	Compensatory effect
Walther *et al.* (2011)	Knife wear	Sharpness	↑ consumption with wear	Maintenance is critical
DLG TestService GmbH (2017)	John Deere 9800	LOC 4–12 mm	0.49 → 0.46 L·t^{-1}	↓ consumption with ↑ LOC
DLG TestService GmbH (2023)	CLAAS Jaguar 960	LOC 4–12 mm	0.53 L·t^{-1} at 4 mm; 0.47 L·t^{-1} at 7 and 12 mm	Initial decrease followed by a plateau