

Mechanisation and automation trends in modern threshing systems: from stand-alone machines to intelligent combine harvesting technologies

P. Borkar¹, C. Sakhale², R. Tupkar¹ and S. Shelare^{1,3,*}

¹Department of Mechanical Engineering, Priyadarshini College of Engineering, Nagpur- 440019, Maharashtra, India

²Department of Aeronautical Engineering, Priyadarshini College of Engineering, Nagpur- 440019, Maharashtra, India

³Centre for Research Impact and Outcome, Chitkara University Institute of Engineering and Technology, Chitkara University, Rajpura, 140401, Punjab, India

*Correspondence: sagmech24@gmail.com

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Abstract. The mechanical harvesting process commonly known as threshing effects the grain quality, yield recovery, and agricultural profitability. To meet rising global food demands due to population growth along with labour shortages there is a need for efficient and automated threshing systems capable of producing high yields with low loss. This paper will provide a summary of recent advancements in threshing technology and evaluate its overall performance based upon criteria such as: efficiency; ability to accommodate different crops; and level of technology utilised in its design. The classification system used to classify threshing equipment into categories included those related to type of threshing mechanism (drum type, concave type, axial flow type); source of power (electricity, gasoline, diesel, hydraulic fluid, etc.), and type of equipment (single crop, multiple crops, and combine). Previous experimental studies reported that modern threshing systems can achieve high threshing and cleaning efficiencies depending on crop type, machine configuration, and operating parameters. High-capacity axial-flow systems have demonstrated productivity values up to 543 kg h⁻¹ in reported studies, whereas smaller solar- and pedal-operated threshers provide suitable alternatives for smallholder farming systems where affordability and portability are important considerations.

Key words: agricultural machinery, agricultural mechanisation, combine harvesters, multi-crop threshers, post-harvest technology.

INTRODUCTION

Traditionally, threshing has been accomplished by hand using rudimentary devices and labour-intensive methods (Hristova et al., 2026). Methods used to perform threshing in the past involved simply pounding the crops, either by foot or with sticks or flails to dislodge the grains from the plant (Benaseer et al., 2018). Threshing using draft animals (bullocks) was another common practice and was done by having the animals walk over

the spread sheaves on a threshing floor. Although this method was a low-cost method requiring little capital investment, it was very time consuming and demanded a lot of physical effort to accomplish; it also was likely to cause significant grain loss and contamination (Vlăduț et al., 2022).

Mechanical threshing, however, represented a new era of agricultural technology. Mechanical threshers developed in the early days of agricultural technology utilised a rotating drum with pegs, teeth or rasp bars to mechanically remove grain faster and more efficiently than manual methods (Sahu, 2023). This mechanical approach significantly reduced dependence on manual labour and improved threshing capacity. As technology continued to develop, there were several designs created to utilise different types of threshing mechanisms. Examples include the use of spike-tooth threshing, rasp-bar threshing and axial flow threshing to allow for the mechanical separation of grains based on the characteristics of various crops and the operating conditions under which the threshing operation takes place. The integration of the threshing unit into a combine harvester took the process one step further, allowing for the reaping, threshing and cleaning of grains all at once; thus, improving the efficiency of the entire operation and reducing the amount of time spent in the post-harvest portion of the production process (Riaz et al., 2017).

Increasing global food demand has created the need for higher-capacity and more reliable mechanical threshing systems (Niu et al., 2025). Mechanising the threshing process not only increases the efficiency of the operation but also decreases the post-harvest losses, which continue to be a problem in developing countries (Tiguh et al., 2024). Research studies show that the mechanisation of threshing can greatly reduce grain loss compared to traditional hand or animal-powered methods, especially when the machines are adjusted to optimise the speed of the drum, the distance of the concave and the feeding rate of the material to be threshed (X. Chen et al., 2022). Modern threshers are designed to accommodate many different crop varieties and moisture content levels, and are adaptable to fit the scale of farming operations in different agro-climates (Castelein et al., 2022).

There are still challenges to overcome to achieve maximum efficiency in threshing grains across all crops and farming systems (Al-Slevani et al., 2022). Technical problems such as grain breakage, poor separation of grains, excessive fuel consumption and difficulty in maintaining the machines are some examples of areas where improvements are continually being sought (Diordiieva et al., 2025). With increasing labour costs and decreasing availability of trained farmers, the demand for threshing solutions that are both efficient and easy to operate has never been greater. Weather related constraints and the need for timely harvesting during short windows of favourable weather conditions also point to the need for high-speed, reliable threshing technologies. The focus of modernisation efforts therefore includes machine durability, energy efficiency, safety and ergonomics to increase both performance and operator comfort (Jawalekar & Shelare, 2020).

Recent technological advancements are beginning to go beyond simply improving mechanical design. Sensors and electronics are being integrated into advanced threshing machines, and software is being developed to monitor and adjust operational parameters in real-time to minimise grain loss and damage, and maximise through-put (Anukiruthika & Jayas, 2025). The inclusion of threshing systems in precision agriculture applications,

such as GPS-guidance and yield monitoring represent a transition to a ‘smarter’ and more sustainable post-harvest processing environment (Ma et al., 2023). Efforts to electrify and develop lower emission engines are also aligned with international efforts to reduce the environmental impact of agricultural machinery.

The need for modernisation is most critical in smallholder dominated agricultural systems, where access to efficient threshing equipment may greatly enhance productivity and income stability. Portable, multi-crop, low-cost threshers provide practical options for many farmers. On the other hand, large-scale commercial farming operations require high-capacity, automated systems to rapidly process the large volumes of product generated. However, meeting all of these different needs creates both challenges and opportunities for the research community, manufacturers and policymakers.

Although numerous prior reviews and publications have covered the various areas in which threshing mechanism function can be improved (i.e., threshing mechanism, harvesting efficiency, loss during harvesting; loss after harvest) as separate entities, this review will cover them all within an integrated framework for technological advancement. Thus, the current review is also focused on developing a comprehensive technology integration framework that links advances in mechanical design with sensor-based monitoring, adaptive control methods, efficient use of energy and social economic acceptance of new threshing technologies. Therefore, this review represents a move toward a more holistic view of intelligently mechanized threshing systems than has been offered previously in terms of the development of adaptive, sustainable and farmer centered post-harvest approaches.

This review is structured to systematically cover the topic. Following this introduction, the paper provides a classification of threshing machines and discusses their functioning principles to create a technical basis. Next, major technological advancements in design, performance optimisation and adaptability to multiple crops are discussed. The review also studies the various emerging trends like automation, intelligent systems, and integration of this trends with precision agriculture technologies. Factors affecting the efficiency of threshing machines and their economic viability are reviewed to evaluate performance criteria. Operational aspects of threshing machines are evaluated to identify factors that affect machine operation and the adoption of threshing technologies, specifically in developing regions. Lastly, emerging trends, research gaps, and future directions for next generation threshing technologies are identified to provide insight into the direction of threshing technologies in the future.

Through this structured format, the review aims to provide a comprehensive understanding of the evolution of threshing machines, the technological advancements that have shaped their current form, and the innovations that will define their role in sustainable agricultural systems.

REVIEW METHODOLOGY AND LITERATURE SELECTION PROCESS

This review utilizes a systematic literature analysis (structured) to assess new developments in threshing technology, mechanisation, automation and smart/precision agriculture. A comprehensive literature search has been performed with international electronic databases to find all published articles in English relating to threshing machines, post-harvest technology, agricultural mechanization, combine harvesters,

multi-crop threshers, axial flow systems, autonomous and sensor-controlled systems, AI and precision agriculture.

Keywords used include ‘threshing machine’, ‘post-harvest technology’, ‘agricultural mechanization’, ‘combine harvester’, ‘axial flow threshing’, ‘multi-crop thresher’, ‘smart farming’, ‘IoT-based agricultural machinery’, ‘AI-based agricultural automation’, and ‘precision agriculture’. Approximately twenty studies have been evaluated from over twenty studies as being technically relevant and providing performance metrics.

Criteria for selecting studies included: evaluating the effects of threshing machine designs; determining operating characteristics of threshing machines; assessing the performance of threshing machines; evaluating automation technologies; or assessing intelligent control systems for threshing. Studies were not considered if they described non-threshing applications, provided no measurable performance metrics, or insufficiently detailed technical information for comparative purposes.

Key parameters were extracted from each study to determine the impact of various factors on the performance of threshing machines. These parameters are as follows: crop type; type of threshing mechanism; threshing machine capacity; operational environment; degree of automation; required energy input; threshing efficiency; cleaning efficiency; extent of grain damage; and percentage of grain lost during threshing. The collected data have been evaluated and synthesized to document the state-of-the-art in terms of both sustainability and automation of threshing technologies.

Although this review is intended to be an evaluative assessment of recent developments in threshing technologies, it is presented in a structured format as opposed to a traditional systematic review process. Therefore, since the objective of this review was to provide a comprehensive technical description of recent advancements in threshing technologies, the methods utilized here were developed to minimize selection bias by utilizing predetermined selection criteria and focusing on peer reviewed journal articles.

CLASSIFICATION AND WORKING PRINCIPLES OF THRESHING MACHINES

Grain separation by threshing machines is a key factor in achieving low loss and minimal grain damage during processing of crops after harvesting (‘Postharvest Losses Due to Harvesting Operations in Developing Countries: A Review’, 2015). The primary categories used in classifying threshing machines are the crop being processed, power source (e.g., mechanical vs. electrical), and the machine's threshing mechanism. The knowledge of each of these areas of categorisation as well as the underlying mechanisms of operation will allow farmers to select the correct piece of equipment; optimise its use; and enhance efficiency throughout the post-harvest process. Each category represents different factors including crop types; farm size; available energy; and operational needs.

Classification of threshers based on crop and power source

Threshing machines have two primary classifications; crop type and power source. The crop specific thresher is based upon grain size/shape, grain moisture, grain attachment strength and plant characteristic. Cereal threshers, which are most commonly used for wheat, rice, barley and sorghum, remove small grains from panicles/ears via a

moderate amount of force/rubbing action (Looh et al., 2025). Rice threshers typically run at slower drum speeds than other cereal types to help minimise grain breakage when processing moist paddy. Maize threshers need significant impact and considerable rubbing forces for separating large kernels from maize cobs (Yang et al., 2021). Pulse and Oilseed threshers, used to process pulse/oilseed crops like soybeans, chickpeas/lentils, sunflower seeds and peanuts/groundnuts, have very specific requirements for their operation as the drum speed, concave clearance and screen/sieve size need to be carefully controlled to avoid damaging the seed coats and causing excessive cracking that could affect both the market price and quality of the crop. In recent years, multi-crop threshers are becoming popular due to the fact that it allows for easy changes in production to accommodate the various crops being harvested by simply adjusting the drum speed, concave clearance and screen/sieve size (Dangora et al., 2026). Threshers are also categorised on the basis of power source. Power sources commonly include manual or pedal-operated machines, various engines, electric motors, tractor PTO drives, battery-powered systems, and hybrid systems. The power source ranges from the very cost-effective small-scale machine for smallholder farmers to very high-capacity commercial scale equipment. Battery/hybrid machines will support a clean agricultural mechanisation system (Mocera et al., 2023).

Types of threshing mechanisms

The threshing mechanism is the central unit of all threshers and defines how grain is separated from plant matter. All of these mechanisms work on various combinations of shearing, rubbing and impact. The spike-tooth threshers have a rotating drum with protruding spikes or pegs. When crop material flows through the space between the rotating drum and the concave, impact is applied to the plant material and it breaks loose and detaches grains. Spike-tooth threshers are the least complicated in terms of construction, the most economical and are used mainly for wheat and other similar crops (Yu et al., 2021). If the spike-tooth thresher is not set up properly, there will be more grain damage than is acceptable. Rasp-bar threshers utilise bars placed on the drum's surface and when the crop material runs against them, a rubbing and beating action takes place. Rasp-bar threshers are best suited for those crops that require moderate threshing and can achieve better grain separation with less grain breakage than the spike-tooth design (Fozilov et al., 2024).

Wire-loop threshers have several wire loops attached with drum for performing threshing. Wire-loop threshers are best suited for delicate crops and can minimise grain damage (Pandiselvam et al., 2022). The hammer mill is a type of thresher which uses high-speed rotating hammers to impact crop materials. The most common uses for the hammer mill are in the dehulling of corn and some pulse processing. Grain damage by hammer mill usage may be minimized if proper controls are put into place to prevent excessive grain breakage (Al-Dawla & Rajab, 2023). Axial-flow threshers are an advancement over the traditional mechanisms of previous threshers; crop material travels along the axis of a rotating rotor. In this process, the threshing and separation of grains occur over an extended period as the crop spirals along the rotor length. The axial flow thresher has provided longer threshing times and greater capacity along with better grain separation efficiency compared to all previously developed designs. Recent

modifications of combine harvesters have broadened the applications of these machines to various types of crops (Khater et al., 2023). Khater et al. (2023) developed modified rice combine harvester for using in cutting and binding wheat. The authors were achieved binding efficiency upto 98.80% using developed machine and also significantly reduces the harvesting loss. Axial-flow threshers are commonly found in modern combine harvesters and are often integrated into the combine harvester (Wu et al., 2025).

The Fig. 1 shows the difference in design of the various cylinder types that each cylinder uses to exert pressure on the crop. The spike tooth and hammer mill cylinders tend to be much more aggressive than the other cylinders therefore are suited for harder to thresh crops however may also cause additional seed damage. The wire loop cylinders will be less damaging to seed therefore more appropriate when threshing delicate seeds. The rasp bar and angle bar cylinders have an equal amount of rubbing and beating action therefore can be used as a general-purpose cylinder for most grain or multi-crop threshers (Kabir & Fedele, 2018).

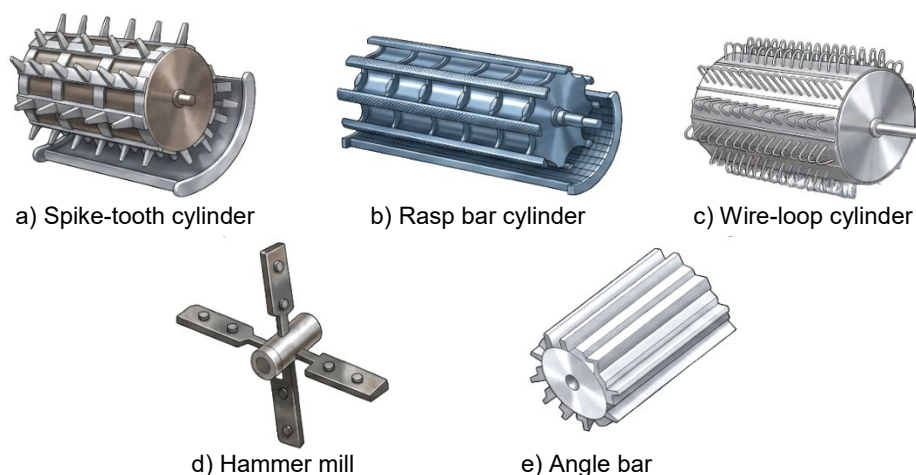
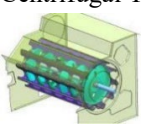


Figure 1. Types of threshing cylinders (Kabir & Fedele, 2018).

A threshing machine can be made in different ways; however, it functions similarly when using similar procedures as follows: feeding, threshing, separating and cleaning. First the crop material is evenly fed into a hopper or conveyor to prevent an overload. Then the crop material goes around a rotating drum or rotor with a stationary concave and the grain is separated from the straw, husk, pod, cob etc., due to the impacts (force), rubbings (friction) shearings (cuttings) and frictional forces. Next the threshed product is moved to the separation area which removes larger straw and trash products allowing grain and smaller materials to pass through the holes of the concave. Lastly, the final step involves cleaning the grain, that has passed through the separation unit, utilising a sieve and fan/blower to remove any remaining chaff, dust, and other lighter impurities. Table 1 summarises the various types of the of threshers.

Table 1. Summary of thresher types

Type	Mechanism	Common CropsContexts	
Drum Threshers 	Rotating drum with paddles/spikes to beat crops	Wheat, Barley, Rice	Small to medium-scale farms, dry crops (Wang et al., 2023)
Axial Flow Threshers 	Rotor and spiral mechanism to move crop material	Wheat, Corn, Soybeans	Large-scale farms, diverse weather conditions (Niu et al., 2025)
Rotary Threshers 	Rotating drum or cone for threshing and separation	Rice, Wheat, Corn	High throughput, wet conditions, commercial farming (Zhang et al., 2022)
Multi-Crop Threshers 	Adjustable settings for different crops	Wheat, Rice, Barley, Legumes	Smallholder farmers with diverse crops (Praveen & M., 2025)
Centrifugal Threshers 	High-speed rotating discs create centrifugal force	Corn, Rice, Beans	Large-scale, dry crop farms (Wu et al., 2025)
Power Threshers 	Powered by tractor or engine	Multiple crops	Large-scale commercial agriculture, powered by tractors (Kumar et al., 2025)
Combine Harvesters 	Integrated machine for reaping, threshing, and separating grains	Wheat, Corn, Soybeans, Rice	Large-scale mechanised commercial farming (Al-Slevani et al., 2022)
Horizontal Threshers 	Horizontal rotating drum for threshing and separation	Wheat, Rice, Millets	Rice, long-stalk crops, commercial farming (Yuan et al., 2024)
Pedal/Hand Threshers 	Human-powered mechanical threshing	Rice, Maize, Millets	Smallholder, subsistence farming, limited resources (J et al., 2021)

TECHNOLOGICAL ADVANCEMENTS IN THRESHING MACHINES

The modern threshing machine has made great strides in developing from a basic device for separating grains to an efficient, long-lasting, versatile, and performance-based unit. The improvements made in threshing machines directly address many of the significant problems associated with post-harvest processing including: (1) grain loss; (2) grain breakage; (3) excessive energy usage; (4) labour availability; and (5) the requirement to process a variety of crops under different conditions found within fields. Most recent innovations related to threshing machines include: (1) enhanced threshing mechanisms; (2) improved separation and cleaning systems; (3) ability to handle multiple crops; (4) increased production rates; (5) greater energy efficiency; (6) increased portability; and (7) reduced grain damage.

One of the areas of greatest potential for improvement involves the design of the threshing drum and concave. The drum and concave are the most critical parts of the threshing mechanism. A large number of modern threshing machines incorporate variable speed drive units that enable the user to adjust drum speed based upon the characteristics of the crop being processed, its moisture content, and the conditions present in the field (L. Chen et al., 2024). Improved rake tooth, rasp bar, and axial-flow rotor designs provide for a more consistent pounding and friction action when processing the crop, thereby increasing the efficiency of the threshing process while decreasing mechanical injury to the crop (Wu et al., 2025). Additionally, wear resistant materials have extended both the service life of individual machine components and provided for more reliable and consistent machine performance. Like drum speed, users can now select and interchange various concaves, depending on the fragility of the crop, particularly those such as pulse crops and oilseed crops.

Separating and cleaning grain separation systems have undergone a considerable amount of change. Many modern threshers utilise improved straw walk systems, axial-type separators, larger separation surface areas, adjustable blow fan capabilities, and multi-stage sift systems to more efficiently separate and clean the chaff, straw, dust, etc. removed from the grain during processing (Agnew, 2024). Users of modern threshers can also adjust air flow rates to meet varying size requirements while maintaining minimum amounts of lost grain. There are several types of modern threshers available that contain features such as pre-cleaners, enclosed cleaning chambers and dust collection systems, all of which contribute to producing cleaner grain for storage and/or marketing by providing a safer environment for operators and better environmental conditions.

A significant development in the threshing is multi-crop and high-capacity threshers. Multi-crop threshers use adjustable drum speed and replaceable concaves, interchangeably selectable sieves, and modules to allow for a single machine to be able to process multiple types of crops including cereals, pulse crops, oil seed crops, and others (Dangora et al., 2026). As mentioned previously, this allows smaller scale and intermediate level producers to eliminate their needs for purchasing numerous crop specific threshers. Commercial agriculture uses high-capacity threshers that use wider drums, longer rotors, heavier duty feed systems, sturdier frame constructions, and heavier duty machine components to process greater volumes of crops rapidly. For example, in the case of combine harvesters, advanced axial-flow and hybrid threshing systems

combine harvesting, threshing, separation and cleaning functions together into one process resulting in faster and lower loss operations.

The move towards sustainable farming practices has resulted in two main considerations when it comes to designing new threshing systems in the years to come: energy efficiency and portability. The amount of energy that is needed to run a thresher may be significantly decreased by improving the efficiency of its belt drive system (Tupkar et al., 2025); optimizing its gearing arrangement; using lighter materials; or improving how it feeds grain into the threshing chamber. There are many ways that mechanical energy loss can be minimized during the threshing process such as the use of electric powered threshers which have variable frequency drives (VFDs). VFDs allow the user to control the speed at which an electric powered thresher operates based upon crop condition and other factors related to processing. With increased emphasis on decentralized agriculture mechanization by using battery assisted and solar powered threshers, also there is a decreased reliance upon non-renewable fuels. However, while electrifying the thresher has some environmental benefits over traditional fossil fuel-based systems, those environmental benefits need to be assessed in terms of the entire lifecycle of the machine including but not limited to, operational emissions; generation methods used to produce electricity; production processes for batteries; manufacture of the machine itself; maintenance costs associated with keeping it running; and disposal at the end of its operating cycle.

Modern threshers are improving machine control and decreasing grain loss/damage while also improving crop flow. Examples include adjusting drum speed, changing concave clearances, sealing grain passage ways inside the machine, improving feeding mechanisms and optimising interior surfaces to minimise incomplete threshing/ spillage/ breakage/ separation losses. Future models may also contain grain loss sensors/monitoring systems that will notify operators or automatically make adjustments during the operation. Overall, advancements in technology continue to improve threshing efficiency/grain quality/machine durability/energy usage/farmer profit margins while providing a base for integrating future technologies/sensors/sustainable agricultural systems (Looh et al., 2025).

AUTOMATION, SMART SYSTEMS, AND PRECISION INTEGRATION

Modern threshing equipment has evolved into machines that are able to control and monitor many of their operational parameters (i.e., drum speed; concave clearance; airflow; feed rate) in ‘real-time’ through integration with sensor technology and precision controllers (Yu et al., 2024).

Sensor-based monitoring

Automating threshing systems using sensor technology helps increase the efficiency of threshing operations. Sensors for speed, load, grain loss, moisture, vibration and temperature allow modern threshers to continuously assess their performance on a number of levels including how efficiently they are removing grains from the crop (drum/rotor), as well as how much grain is being lost during this process (grain loss). The continuous data provided by these sensors allows operators to adjust the drum's rotational speed in real-time as well as make adjustments to the clearance of the concave,

which provides optimal conditions for the threshing process. In addition, these sensors provide data that can be used to optimise the amount of force applied to each individual grain, minimise potential overloads and prevent excessive mechanical wear due to friction and other forces, ultimately increasing a threshing system's operational reliability, operational efficiency and overall production capacity.

IoT and data-driven performance optimisation

IoT enabled threshers can send production rates, losses in grains, use of fuels, vibrations and efficiencies from cleaning operations back to a cloud system where they will be analysed. Analysis of this information allows for the optimisation of drum speed, concave clearance and feed rate; also, it provides predictive maintenance, real-time performance tracking and the ability to integrate with other agricultural management systems allowing for more efficient, data-driven decision making and reduced down time (Qiu et al., 2022).

AI applications in threshing

Artificial Intelligence (AI) is improving threshing equipment using algorithms that examine real-time input from sensors and Internet of Things (IoT) technologies. This enables the threshing system to automatically optimise machine performance; including rotor speed, concave clearance, and fan air flow based upon the type of crop being harvested, its moisture level, and grain quality. The algorithm also utilises machine learning to determine patterns of grain loss and energy usage and utilise computer vision technology to assess how clean the grains are. Predictive Analytics enable predictive maintenance for a continuous running threshing operation (Guan et al., 2022).

Integration with precision agriculture and combine harvesters

The new combine harvesters are using integration of precision agriculture to combine in one system of all three processes that were separate: harvesting, threshing and cleaning. They use GPS and the data from the yield monitors to measure how well they are performing through the entire process. Then, using the data collected on the density and moisture levels of their crops, they can adjust their operating parameters. With automation and IoT connections to each piece of equipment and AI capabilities, farmers will be able to monitor their combines in real-time, perform predictive maintenance, and make adjustments for optimal operating conditions. This should increase efficiency, improve grain quality, and provide a means for long term sustainability in farming.

Recent advances in smart technology and automation have resulted in a quantifiable improvement in both combine harvesting and threshing performance as shown in Table 2. It has also been observed that an advanced, sensor-driven system using an entrainment loss sensor and an intelligent control algorithm may be able to reduce grain loss by up to 30–45% over conventional manual adjustments of the operating parameters (i.e., concave clearance and drum speed) for each harvest pass. The above-described systems are able to make continuous, real-time adjustments to the operational parameters (e.g., concave clearance and drum speed), which enhances the overall efficiency of the threshing process while simultaneously reducing breakage and separation losses during the threshing process.

Table 2. Automated Threshing Systems and Performance

Technology/System	Crop/Machine	Performance metrics	Practical benefit	Reference
Sensor + fuzzy neural network PID control	Maize combine	Entrainment loss ↓43.75%; Cleaning loss ↓32.79%; Breakage ↓2.39%	Reduced grain losses	(Yu et al., 2024)
Machine vision (Mask R-CNN)	Rice combine	Precision 92.49%; Recall 88.63%; Accuracy 91–97%	Automatic quality monitoring	(Guan et al., 2022)
IoT-based monitoring system	Combine harvester	Condition recognition accuracy 97.46%	Predictive monitoring and optimisation	(Qiu et al., 2022)
RTK-GPS autonomous navigation	Rice combine	Tracking error 0.038–0.052 m; Field work efficiency (time-based) 76.7%	Improved harvesting precision	(Lee et al., 2023)

The results from the smart threshing technology are two-fold: first there is the intelligence level of the system as measured by the ability to intelligently perceive as shown in Fig. 2, a, secondly, there is an improvement in operations as shown in as shown in Fig. 2, b. However, these two categories of evaluations represent different criteria for measuring the effectiveness of the system, therefore they should not be used to rank the systems based on one or both of these factors. Smart machines using artificial intelligence have shown very good predictive capabilities such as being able to recognize conditions with which the system is operating at an accuracy of 97.46% and having vision/inspection capabilities that have precision/recall rates over 88%. In contrast, smart machines that use adaptive controls have shown measurable improvements in how well they operate such as reductions in entrainment loss of 43.75%, cleaning loss of 32.79%, impurities of 5.08% and grain breakage of 2.39%. These improvements demonstrate the ability of smart machines with control mechanisms to improve operationally by adjusting parameters for threshing and reducing physical loss, rather than showing how well the machine performs compared to its classification ability.

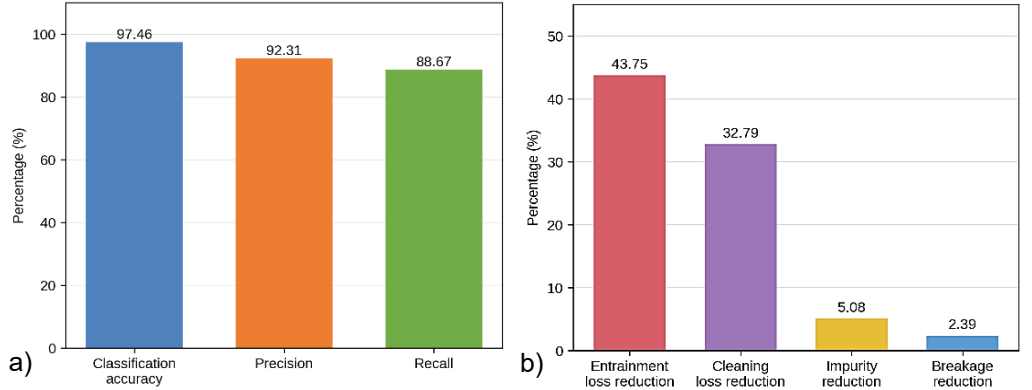


Figure 2. Reported (a) AI capability and (b) operational improvement indicators of smart threshing and combine systems.

As such, Fig. 2 is intended to show the differences in the types of results achieved by smart threshing systems rather than provide a comparison/ranking based on the percentage figures of the different systems.

Deep learning-based models (such as Mask R-CNN) have recently achieved high accuracy levels (greater than 90%) in detecting foreign objects within grain, allowing for reliable, real-time monitoring of grain quality/ cleanliness. The accuracy achieved with this system enables fully automatic adjustments of air flow and sieve settings in order to enhance grain quality while minimizing subsequent post-harvest processing operations.

The use of predictive analysis by means of IoT technologies enables further improvements to the operational efficiency of farm equipment through the integration of multi-source sensor information and cloud based analytical functions enabling optimization of the performance of the machine as well as providing predictive capabilities for planned maintenance activities. Analysing telematics data shows that optimizing the operation of harvesters is capable of reducing the CO₂-eq emissions of each harvester by approximately 1.3 metric tons annually. Thus, this process results in positive environmental effects. Autonomous combine systems incorporating RTK-GPS maintain centimetre-level positioning accuracy, resulting in an average of 3–5 cm working error and improved field efficiency and reduced overlap loss.

Critical assessment of smart threshing technologies: opportunities and limitations

Although there has been an advancement in threshing using automation, IoT and artificial intelligence (AI) there are many barriers that prevent them from being widely used. Many current ‘smart’ threshing systems focus on adjusting machine settings (drum speed, concave clearance, air flow, etc.) to optimize the process, and they rely heavily on accurate calibrations of sensors and access to crop specific data. As shown in studies done on sensor-based control systems there is a measurable reduction in grain loss and an improvement in stability of the operating system. Unfortunately, when you put these systems out into real world conditions where all variables change (crop moisture, soil condition, temperature, operator practices), it becomes challenging to provide consistent results.

Although many studies have shown extremely high threshing and cleaning efficiencies in laboratory tests as well as in highly controlled field tests; however, those test results should be viewed with caution if we want to apply them to agricultural production as it is carried out today. In order to achieve high levels of efficiency (e.g., high throughput and/or low loss) in either a laboratory setting or an ‘optimized’ field test, there are usually very specific parameters being maintained such as crop moisture at uniform levels, constant feeding rate of the crop to the machine, optimal drum speeds for the particular machine used, proper clearance between the drums and the concaves, and professional-level machine operation. In contrast to the controlled environment found in laboratory settings or even in field tests where every effort was made to maintain consistent conditions, actual farms have significant amounts of variation in terms of crop type, weather conditions, soil conditions, operator experience, maintenance practices and the availability of technical support. As a result of this variability, it is likely that the highest technical potential demonstrated by a given technology will not necessarily reflect its ability to perform consistently across all possible farming systems.

Further the distinction between technology technical potential and its adoption is provided as listed in Table 5. An example would include a new threshing technology demonstrating a much higher level of cleaning efficiency as well as lower grain loss than existing machines, yet failing to gain widespread acceptance among producers because of the high initial investment required, complexity associated with operating the machine, high maintenance needs, limited number of experienced personnel available to operate the machine, and limited availability of repair services. Small and marginal farmers frequently place additional importance on issues related to affordability, ease-of-use, reliability and adaptability to other crops when making decisions regarding new machinery purchases versus attempting to achieve the highest levels of efficiency from their equipment. It follows that in addition to meeting technical requirements for efficient threshing and cleaning performance, developing successful commercial implementations of advanced threshing technologies also require that they meet certain criteria related to economic viability, user acceptance and suitability for use in various types of farming operations.

Therefore, future research should move away from simply evaluating threshing equipment performance using laboratory scale methods and toward conducting long term multi-locational evaluations of equipment performance over time using various crops, climates and producer groups. These evaluations should utilize standardized methodologies for testing threshing equipment performance; life-cycle cost analyses of the threshing equipment; and design approaches that centre around the needs of the producer.

Although, advancements with threshing systems utilizing artificial intelligence (AI) and the Internet of Things (IoT), have shown great potential to enhance real-time monitoring, adaptive control, and predictive maintenance through the use of advanced technology; the reliability of all threshing system technologies are largely dependent upon the quality and effective management of electronic components used in the overall design and function of an automated agricultural system. Sensors and electronic modules in agricultural equipment are showing the high level of operational stresses. High levels of dust that develop from crop residue, continuous vibrations from mechanical motion, fluctuating temperatures, and extremely humid environments during harvest create an environment where sensors can become disoriented causing a loss of data integrity. This loss of data integrity will ultimately lead to a decrease in the accuracy of measurements taken by these sensors. As a result, it is crucial to implement a program for regularly calibrating critical sensors associated with measuring factors such as grain-loss, moisture content, vibration rates, temperature variations, and applied loads. The implementation of routine preventive maintenance activities, which include inspecting and cleaning sensor surfaces, inspecting wiring and connectors, updating firmware and conducting periodic diagnostic testing will help prevent unforeseen component failures. Unfortunately, performing these maintenance functions at remote locations are often difficult or impossible to perform because there are typically no trained technicians available at the location, there are rarely sufficient spare electronic parts available and there are usually no digital communication resources present. To successfully adopt smart threshing technologies, farmers need to be provided with robust, durable and weather resistant sensors along with self-diagnostic features. Furthermore, successful adoption of smart threshing technologies requires providing farmers with adequate

training, developing local technical support networks and creating simple-to-use user interfaces. Future development efforts should concentrate on low-maintenance sensor technologies, edge-based data processing and autonomous calibration techniques to enhance both the reliability and accessibility of automated agricultural systems for small and remote farming communities.

Another limitation with AI-driven threshing systems is they require access to many different kinds of data sets. Many of the current machine learning models are tested in either laboratory-controlled environments or small-scale field testing; this can limit their usability across different geographic areas and different crops. Additionally, while AI provides greater opportunity for optimization of the threshing system, this comes at the cost of increased complexity and possibly greater maintenance costs than traditional mechanical systems. Thus, the enhanced technology of modern threshers does not automatically equate to better usage by small holder farmers who place importance on affordability, repairability, and ease of use.

It seems there is a correlation in the cost of an automated machine with the amount of automation built into it. Larger commercial operations can financially justify purchasing fully automated high tech combine harvesters equipped with GPS, machine vision and predictive analytics. The justification for investing in smart threshing systems can be through higher yield/acre and lower operating cost. However, small and marginal farms will want less expensive, lighter weight, more portable and able to perform many different functions. In order to ensure successful implementation of new technologies for small and marginal farmers, future developments should include simple, affordable, portable and adaptable to local needs rather than focusing solely on creating autonomous systems.

Sustainable aspects of smart threshing need to be compared for the entire product cycle. Electric drive motors, optimal operating modes and decreased fuel consumption reduce operational emissions. Battery production, electronic component replacements, sensor replacements and other infrastructure associated with digitization need to be included in total life cycle assessments of smart threshing. To offer an additional viewpoint regarding the growth in threshing technology, this study compares different threshing methods for their operational mechanics, advantages over earlier designs, disadvantages to earlier designs, and barriers to adoption as well as areas for continued research. Table 3 illustrates the trade-offs among the four characteristics mentioned above.

Limitations of comparative performance assessment

Although this literature review comprehensively evaluates recent developments in threshing technology, it is difficult to make a direct quantitative comparison amongst previous studies that report threshing behaviours and machine performances based on considerable variability in experimental conditions. Crop characteristics such as crop type, grain properties and moisture levels significantly affect threshing behaviour and machine operation. Additionally, there are significant differences in machine configurations, threshing mechanisms, operational parameters, testing environments, and measurement methods used for evaluating performance in various studies. The same performance metrics (e.g., threshing efficiency, cleaning efficiency, grain loss, grain

damage, and throughput) may not be consistently evaluated by each study. Therefore, the range of performance values and percentage improvements presented in this literature review should be understood as specific to individual studies with their own unique operating conditions; they cannot be assumed to represent universally accepted performance standards for different types of crops and agricultural systems. To provide for increased reliability in comparing threshing technologies and encouraging broader implementation of new threshing technologies, future research efforts should include developing consistent testing protocols, establishing standard performance criteria for evaluation, and conducting large scale validation tests on-site in fields.

Table 3. Critical comparison of conventional and smart threshing systems

Technology	Principle	Advantages	Performance	Limitations	Adoption	Research need
Manual Threshing	Manual/animal operation	Low cost	Low capacity, high losses	Labour intensive	Small farms	Low-cost alternatives
Mechanical Threshers	Drum-based separation	Less labour, higher output	Improved efficiency	Fuel use, operator dependency	Small–medium farms	Energy-efficient designs
Multi-Crop Threshers	Adjustable settings	Crop flexibility	Moderate efficiency	Frequent adjustments	Diverse small farms	Auto-adjustment systems
Combine Harvesters	Integrated harvesting and threshing	High-capacity	High productivity	Expensive, high-energy use	Large farms	Affordable automation
Sensor-Based Threshers	Real-time monitoring	Better control	Reduced losses	Sensor maintenance	Medium–large farms	Low-cost sensors
IoT Threshers	Connected monitoring	Remote operation, prediction	Reduced downtime	Connectivity issues	Commercial farms	Rural IoT solutions
AI-Based Threshers	AI-driven optimization	Autonomous control	Higher efficiency potential	Cost and data limitations	Limited smallholder adoption	Explainable AI and digital twins

PERFORMANCE EVALUATION AND OPERATIONAL CONSIDERATIONS

The overall performance of agricultural threshing machines is measured in terms of technical, operational, economic and safety criteria. To be able to produce the best possible grain yield with least loss, energy efficiently and economically it is important that there is an effective method of assessing machine performance (Sharma et al., 2022). Factors relating to operation of the machine which can have a significant impact on threshing performance are factors related to crop type, moisture levels of the crop, feed rates and machine setting etc. Therefore, a comprehensive assessment methodology will enable researchers, manufacturers and farmers to develop the most productive and sustainable designs and operating methods for threshing machines.

Threshing and cleaning efficiency

Threshing efficiency is a measure of how well a machine can remove grains from non-grain materials (straw, pods etc.), usually in terms of percent. Factors which affect threshing efficiency are; drum speed, concave clearance, feed rate, crop moisture, design of threshing mechanism (L. Chen et al., 2024). Although, the process of threshing, separating and cleaning happen one after another inside the threshing machine; they are defined as the different operation stages of the threshing machine and therefore, can't be replaced for each other. The primary purpose of evaluating the efficiency of threshing is the evaluation of how effectively grain separates itself from crop material. The primary purpose of evaluating the efficiency of separating is the evaluation of how effectively separated grains are retrieved from straw and residue. The primary purpose of evaluating the efficiency of cleaning is the evaluation of how effectively residual contaminants on the retrieved grains are removed. The most effective way to optimise cleaning efficiency is with fan speed and sieve opening (Wu et al., 2025). Most modern threshers have adjustable controls allowing an operator to adjust all parameters according to specific crop types, moisture levels, and field conditions for maximum grain separation, minimum breakage, high quality clean product and continued consistency in operation. Reported efficiencies for a given technology depend heavily upon both experimental design and the specific operational characteristics of a system. Therefore, when comparing different technologies, in addition to considering the highest efficiencies possible with each, it is also essential to evaluate and compare their robustness, adaptability, cost-effectiveness, and performance stability under typical or normal working conditions.

Higher threshing efficiency indicates better grain detachment performance with minimum unthreshed grain losses. Threshing efficiency is calculated by η_t as given in Eq. (1):

$$\eta_t = \frac{W_s}{(W_s + W_u)} \times 100 \quad (1)$$

where η_t = threshing efficiency (%); W_s = separated grains collected (kg); W_u = unthreshed grains remaining with straw/pods (kg).

Cleaning efficiency is calculated based on the reduction of impurities after the cleaning operation. It is calculated by η_c as given in Eq. (2):

$$\eta_c = \frac{(I_i - I_o)}{(I_i)} \times 100 \quad (2)$$

where η_c = cleaning efficiency (%); I_i = impurity content before cleaning (kg); I_o = impurity content after cleaning (kg).

Grain breakage and loss assessment

Grain breakage and loss, which represent critical efficiency measures of a thresher's function, determine the extent to which mechanical force is able to damage kernels. Grain breakage have impact on the both the market price of grain and its seed viability. In addition to broken kernels, losses from threshing also result in unthreshed grain, separation loss, and cleaning loss (Looh et al., 2025). The modern technology now available minimises such losses through adjustments of drum speed, concave clearance, sealed pathways for grain, and real-time computerised systems that enable timely identification and adjustment for operational efficiencies.

Low grain damage is essential because broken grains reduce market value and seed viability. Grain damage is calculated by D_g as given in Eq. (3)

$$D_g = \frac{W_\beta}{W_t} \times 100 \quad (3)$$

where D_g = grain damage (%); W_β = broken/damaged grains (kg); W_t = total grain output (kg).

Grain losses generally include unthreshed grain loss, separation loss, and cleaning loss. Grain loss is calculated by L_g as given in Eq. (4)

$$L_g = \frac{W_l}{W_i} \times 100 \quad (4)$$

where, L_g = grain loss (%); W_l = weight of lost grain (kg); W_i = total grain entering machine (kg).

Throughput capacity and energy consumption

The performance metrics of threshing machines evaluate how well these machines are suited to different scale farming operations in terms of production rate (throughput), as well as its ability to keep up with immediate post-harvest needs to avoid crop spoilage (Akendola et al., 2025). The throughput is influenced by several machine design parameters such as drum width, rotor length, feeder design and the amount of power that feeds the machine. Uniform, continuous feeding of a threshing machine maximises the production potential of a machine while too much material fed into the threshing process at one time reduces efficiency, increases grain loss and may also cause damage to the machine. The energy consumed by the threshing machine is compared to the total output produced by the machine. Therefore, optimising transmissions, drum designs, reducing friction etc., will provide maximum efficiency in using energy on all threshing and separating machines whether they are powered by an internal combustion engine or electric motor (Pan et al., 2025). All high-throughput threshing machines have a common goal; to maximise their production capability while using a sustainable amount of energy. Several key performance metrics exist for measuring the performance of threshing and separating equipment. These performance measures are threshing efficiency, cleaning efficiency, grain breakage, grain loss and energy usage. This enables comparison among various types of threshing/separating equipment, crop applications and sources of power.

Throughput capacity depends upon the feed rate, drum size, rotor speed, crop type, and machine type. Throughput capacity is calculated by T as given in Eq. (5)

$$T = \frac{W}{t} \quad (5)$$

where T = throughput capacity (kg h⁻¹); W = processed material mass (kg); t = operating time (h).

A lower specific energy consumption indicates improved energy efficiency of the threshing system. Specific Energy Consumption is calculated by SEC as given in Eq. (6)

$$SEC = \frac{E}{W} \quad (6)$$

where, SEC = specific energy consumption (kWh kg⁻¹); E = energy consumed (kWh); W = processed material mass (kg).

Although total throughput capacity and separation efficiency can be considered typical key performance indicators for threshing systems, to assess the sustainability of threshing systems it is necessary to normalize the energy used during operation with respect to the quantity of processed material. Thus, the specific energy consumption (SEC) of a threshing system, measured in units of kWh t⁻¹ or MJ t⁻¹ of processed grain, offers an additional metric that is capable of facilitating comparative assessments of various threshing technologies being operated under differing scale-based conditions. The SEC represents the energy needed to process 1t of agricultural product and combines the impacts of the design of the threshing equipment, its power supply, the conditions under which it operates and its production rate. While high-throughput systems based upon axial flow technology and combines are able to provide higher rates of productivity than lower-throughput systems such as those powered by solar, foot or electrical drives; these latter systems will typically require less energy per unit of time to operate. However, while the former systems have potentially larger capacities for processing materials, they also rely upon achieving equivalent reductions in terms of energy-intensity. Furthermore, because future research needs to account for all factors affecting the sustainability of a threshing system (i.e., energy usage, through put, threshing efficiency, cleaning efficiency, and grain loss) in order to facilitate valid comparisons among them; we recommend that researchers include data related to each of these parameters when reporting results from their investigations.

Table 4 summarises quantitative performance measurements that have been used to report the operating capacity and efficiency of some of the selected threshing equipment. The results from each of these studies can however be difficult to compare numerically since they are based on evaluation of the equipment using different crop types, moisture levels, feeding rates, configurations (including engine type), power source(s) and experimental protocol. Thus, the productive outputs presented by these studies are indicative of how well each of these pieces of equipment performed in its respective operational context; and do not indicate a standard basis of comparison to determine which is superior.

As demonstrated in Table 4, each crop-machine combination has a specific throughput capability. However, due to the variety of factors involved with each threshing system that can affect productivity, these values should not be considered as a measure of performance, but rather as an observation of what was done in the field. The differences observed among the various threshing systems are the result of multiple interactions, such as crop properties, machine design, type of threshing unit, feeding rate, method of power supply, operating parameters, and methods used for evaluating. Consequently, the greater productivity value associated with the axial-flow threshing system is indicative of its suitability to meet high volume processing needs under optimal operation, while lower productivity threshing systems have potential for providing increased portability and/or energy self-sufficiency. To make a valid comparative analysis of technology, it would be necessary to use the same crop material, operate at the same conditions, and follow the same evaluation protocol.

Table 4. Performance of selected threshing machines across crops

Crop / Machine type	Operating condition / configuration	Capacity / productivity	Threshing efficiency (%)	Cleaning efficiency (%)	Grain damage / loss (%)	Reference
Solar-powered multi-crop thresher on soybean	Cylinder peripheral speed: 13.62 m s ⁻¹ ; feed rate: 4.3 kg min ⁻¹ ; concave clearance: 20 mm; spike type 3	116.64 kg h ⁻¹	96.3–99.9	86.68–93.05	NR	(Harerimana et al., 2024)
Pedal-cum-solar paddy thresher	Drum speed: 290–310 rpm; paddy moisture: 18.45%	Solar: 231.67 kg h ⁻¹ ; pedal: 66.63 kg h ⁻¹	Solar: 98.67–99.58; pedal: 97.01–98.54	NR	NR	(J et al., 2021)
Axial-flow paddy thresher	Optimised louver angle, peripheral speed and feed rate	543.13 kg h ⁻¹ grain output	98.6	97.27	Broken grains: 0.11; non-collectable loss: 0.01	(Parihar et al., 2022)
Locally developed soybean thresher	Variable operating speed conditions	81.2–96.4 kg h ⁻¹	74.62–93.67	NR	2.0–4.7; median damage: 2.7	(Akendola et al., 2025)
Modified groundnut combine with rubber-vane stripping drum	Modified threshing drum and stripping drum	NR	94.2	NR	Pod damage: 1.6	(Pan et al., 2025)

Table 5. Optimisation parameters reported for threshing systems

Crop / Machine	Method / model	Optimised machine parameters	Optimised performance result	Main interpretation	Reference
Chickpea peg-tooth thresher	Response Surface Methodology (RSM)	Cylinder speed: 10.63 m s ⁻¹ ; concave clearance: 13.74 mm; feed rate: 240 kg h ⁻¹ ; moisture: 12% w.b.	Grain damage: 3%; threshing efficiency: 98.3%; germination: 84.29%	Lower cylinder speed and controlled moisture reduce seed damage while maintaining high threshing efficiency.	(Salari et al., 2013)
Gap-adjustable corn thresher	Prototype testing and parameter optimisation	Adjustment gap: 30 mm; drum speed: 300 rpm; feed rate: 1.5 kg s ⁻¹	Cleaning rate: 99.07%; kernel breakage: 2.23%	Adjustment gap had the strongest effect on cleaning rate and kernel breakage.	(Xing et al., 2024)
Corn seed bionic thresher	Quadratic regression orthogonal rotation design	Differential roller: 90 rpm; discrete roller: 350 rpm; threshing roller: 350 rpm; discrete and threshing gap: 4.6 mm	Broken rate: 0.226%; net removal rate: 99.317%; corncob integrity: 100%	Bionic “first discretization then threshing” reduced grain damage while maintaining high removal efficiency.	(Zhao et al., 2023)
Maize thresher with automatic gap control	Feed-rate-based electro-hydraulic control	Optimal threshing gaps: 43, 47 and 51 mm at feed rates of 6, 8 and 10 kg s ⁻¹	Threshing efficiency increased by 7.32%; broken grain reduced from 5.21% to 3.85%; entrainment loss reduced from 0.29% to 0.21%	Automatic concave-gap control improved quality under fluctuating feed rate, though power use rose by 3.45%.	(Fan et al., 2022)
Soybean pneumatic cleaning-circulatory thresher	Floating-speed-based pneumatic cleaning design	Fan speed: 526–611 rpm; screen vibration frequency: 276–320 Hz	Mean straw debris: 0.70%; cleaning loss: 0.30–0.32%	Air-suction and circulation cleaning reduced impurity and cleaning loss.	(Wu et al., 2025)

Fig. 3 compares the performance-capacity relationship of certain threshing technologies; it is not an actual comparison of each specific value. A comparison of the two systems indicates axial flow threshers can perform significantly better regarding throughput (the quantity of material processed) and head removal at larger throughputs, making them more suitable for use in commercial operations. In comparison, the solar and pedal-assisted threshing systems operate with a similar level of efficiency; however, they are capable of processing less volume. As such, solar and pedal-assisted threshing systems would appear to be more suited for use by small-scale producers whose access to affordable energy is limited.

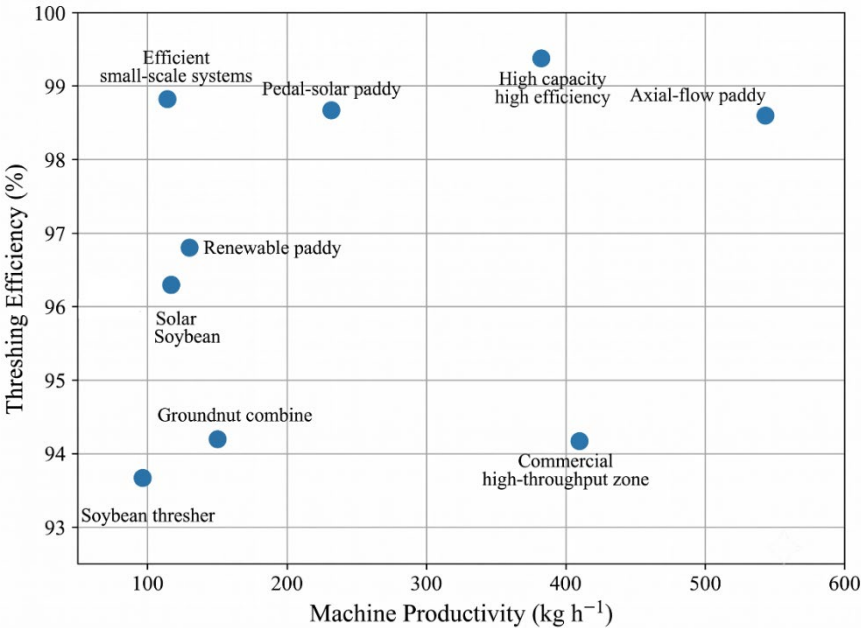


Figure 3. Performance positioning of selected Thresher technologies.

The optimised parameters of some of the most significant studies are summarised in Table 5, which illustrate how adjusting these parameters will increase threshing quality and reduce post-harvest losses.

As seen in the optimised systems of Fig. 4, it is possible to achieve a significant level of separation or cleaning performance with little or no damage to grains if crop specific parameters for each species are applied. The bionic thresher for corn seed shows the lowest recorded broken rate (0.226%), while still showing an effective net removal of 99.317%. The results of these various experiments have shown that controlled clearance, low-impact threshing mechanisms, and staged separation methods may be able to reduce mechanical damage (and maintain high separation efficiency) in crop processing systems. This is an observation about what has been observed in all the data as a common trend, and does not represent testing of or a validation for any one proposed mechanism or theory.

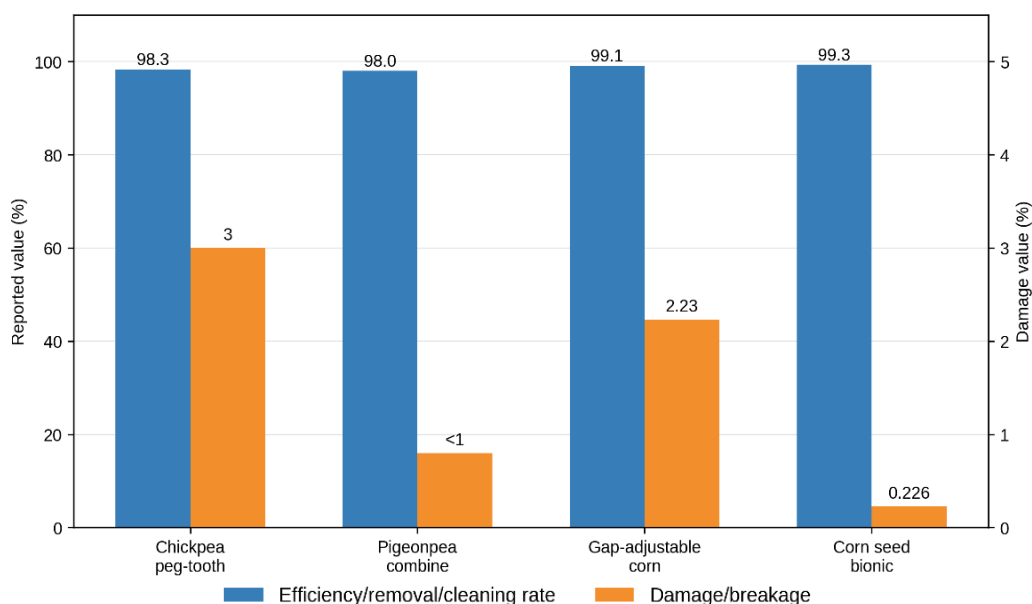


Figure 4. Optimised quality trade-offs between separation performance and grain damage.

Economic feasibility and cost analysis

To compare the economics of different threshing technologies, there needs to be common yardsticks that go further than just initial purchase cost and operating expense. Key factors in comparative assessments need to include such as total cost per tonne of processed grain, annual operating time, machine capacity, break-even utilization and payback period. The most useful measure of the relative costs of threshing machines is likely to be based on the average cost per tonne of processed grain. This can then take into account all fixed costs, depreciation, energy consumption, labor, maintenance and actual production. Machines which are relatively expensive to buy may still be cheaper overall if used to process sufficient quantities of grain. Conversely, machines that could technically have been expected to produce significant reductions in processing costs will fail to do so, if they are utilized below their potential (El Din Abdel Gadir El-Awad, 2012).

Annual operating hours and throughput capacity significantly affect the economic viability of threshing systems. Smaller scale threshers are usually economical options for small-scale farmers due to lower capital investment, portability and lower operating costs. On the other hand, larger machines like axial-flow threshers or combines can only be justified by being operated on a large enough farm to produce large enough volumes of crops each year.

Break-even utilization and payback period are useful measures for assessing how long it takes to recover the cost of an investment by saving labor; increasing productivity; reducing crop losses; and using less energy. Because of differences in machine prices; fuel, electricity and wage rates; crop yields; inflation rates; and local agricultural practices, the costs of different threshing systems cannot be compared without some form of normalization.

Table 6. Adoption, economic, energy and environmental indicators

Study context	Sample / machine base	Key quantitative indicator	Economic / operational result	Implication for review paper	Reference
Rice-wheat thresher adoption in Bangladesh	5,605 households	Adoption: 52.41%; dis-adoption: 13.75%	Larger farms were 31% more likely to adopt; regular extension contact increased adoption by 33%; extension contact reduced dis-adoption probability by 9.3%	Extension access is a major determinant of sustained thresher adoption	(Rahman et al., 2022)
Mechanisation and farm income in Eastern India	2,638 farm households	Thresher adoption increased net farm income by 12%	Overall machinery adopters had nearly 20% higher net farm income than non-adopters	Thresher adoption has measurable income benefits, but lower than motor pumps and rotavators in the cited study	(Rahman et al., 2022)
Combine harvester vs PTO thresher for sorghum in Sudan	44 combine harvesters; 50 PTO threshers	Capacity: combine 6.4 t h ⁻¹ ; PTO thresher 1.1 t h ⁻¹	Operating cost: combine US\$39 h ⁻¹ ; PTO thresher US\$10 h ⁻¹ ; breakeven capacity: 3.1 vs 0.9 t h ⁻¹	Combines suit large farms; PTO threshers suit small holdings and lower-cost operations	(El Din Abdel Gadir El-Awad, 2012)
Agricultural machinery manufacturing in Bangladesh	70 foundries; 800 machinery workshops; 1,500 spare-parts workshops; 20,000 repair workshops	Annual agricultural machinery market: US\$907.5 million	Local production market share: US\$402.7 million; spare-parts market: US\$309.3 million; domestic spare-parts production: US\$237.9 million	Local manufacturing and spare-parts systems are critical for affordable thresher diffusion.	(Alam et al., 2017)
IoT-enabled solar-powered multi-crop thresher	750 W BLDC motor; 1 kW solar PV; 1.5 kWh lithium-ion battery	Threshing efficiency: 93%; cleaning efficiency: 88%; energy requirement: 0.35 kWh per 100 kg crop processed	Energy cost reduced by about 60%; CO ₂ emissions reduced by 100% compared with diesel thresher within the operational system boundary considered in the cited study	Solar-IoT threshers show strong potential for decentralised low-emission threshing	(Praveen & M., 2025)
Redesigned beater wheat thresher in Pakistan	Conventional vs redesigned machine	Weight reduced from 1,600 kg to 1,300 kg; threshing efficiency improved from 98% to 99%	Cleaning efficiency improved from 97.44% to 98.18%; fuel consumption reduced by 1.3 L h ⁻¹	Engineering redesign can improve safety, efficiency and fuel economy simultaneously	(Ahmad et al., 2025)

Therefore, any comparison should first normalize costs from studies conducted in different countries and years. To fully assess the feasibility of different threshing systems, therefore, a full assessment must also look at both the technical characteristics (machine capacity; efficiency; grain loss); and the operational (annual operating time; percent utilization) and financial (total cost per tonne; payback period; break-even point) characteristics.

Safety, ergonomics, and environmental impact

Modern threshing machines have numerous ergonomic and safe components that will protect the operator from hazards and help prevent fatigue. This includes; safety guards, emergency stop functions, protective covers, an adjustable feed table, and vibration dampening systems along with easy-to-read controls. In addition, modern threshing machines also provide noise reduction, dust collection systems, and closed in cleaning areas for better overall operator health. Compliance with current regulations is also achieved through these designs. Additionally, ergonomic improvements are most important at the time of maximum operating usage because extended use of the equipment increases physical strain on the user (Alam et al., 2017).

The integration of both environmental sustainability and operational efficiency has become an increasing factor within modern thresher design. The fuel-efficient engine technology, greenhouse gas emissions reducing technologies, and the development of electric/battery powered thresher models all contribute to a decrease in greenhouse gas emissions. Additionally, sustainable design techniques such as using recycled materials in the manufacture process and designing longer lasting units (throughout its life cycle) minimise waste generation and the negative impacts of environmental degradation. Evaluation of threshers for adoption and evaluation purposes should be based on several factors including but not limited to; costs, energy requirements, ease of access to parts/maintenance, and economic viability to provide a complete basis for which to evaluate threshers under actual field conditions (Ahmad et al., 2025). Table 6 shows the Quantitative adoption, economic, energy and environmental indicators.

The data on the adoption of the thresher technology shown in Fig. 5 indicate that approximately 52.41% of farmers have adopted the rice-wheat thresher technology and 13.75% are using it less than before; therefore, factors such as availability, usability, quality of instruction, and economics can impact continued use. Also, the largest environmental advantages were found using the solar- IoT thresher, which produced approximately a 60% cost savings in operating expenses over diesel-powered threshers. The cited research stated that the solar powered system eliminated all CO₂ emissions directly related to the combustion of diesel fuel during threshing; however, it is important to note that this data only reflects the emissions within the operational boundary of the equipment, and therefore should not be used to indicate that there are no total life cycle greenhouse gas emissions from these systems. As such, the embodied environmental effects of photovoltaic panel manufacturing, battery systems, electronics, manufacturing, distribution, repair and disposal were excluded from this analysis. To fully understand the entire carbon footprint of a solar-IoT threshing system, a full life cycle assessment (LCA) would be needed. As such, there is an urgent need for the evaluation of the adoption feasibility and efficiency of new technologies.

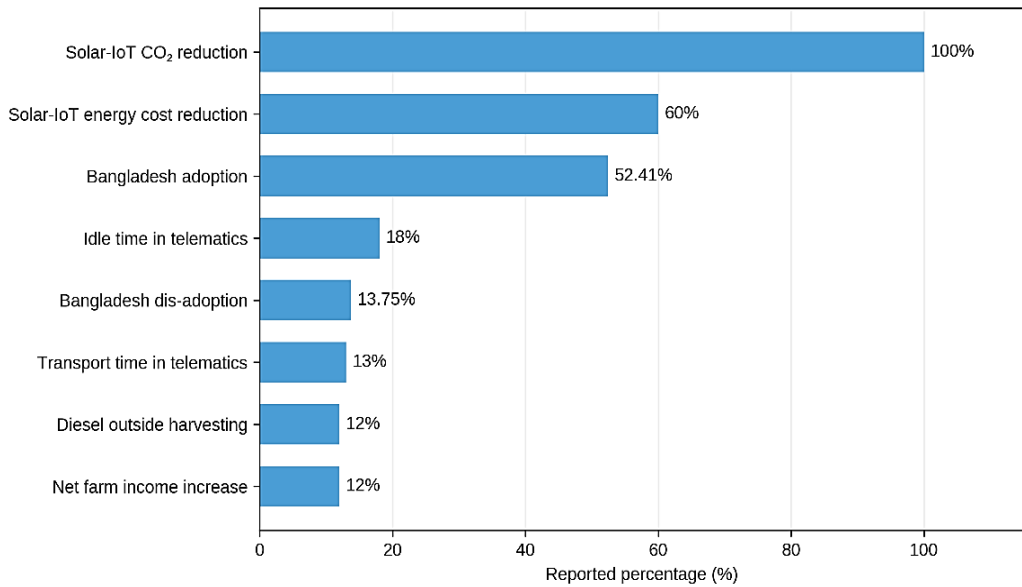


Figure 5. Adoption, economic and environmental indicators relevant to thresher deployment.

The architectural structure of this system (as illustrated by Fig. 6) provides a framework for integrating sensor data from crops and machines with control algorithms based on artificial intelligence, actuators that are adjustable, IoT systems providing real-time analytics for improvement through continuous feedback loops. This illustrates how the reviewed technologies come together: Sensors detect loss, loads, moisture, vibrations and clean grain; Controllers adjust concave gap, drum speed, fan air flow and feed rates; IoT systems provide fleet-wide monitoring and predictive maintenance.

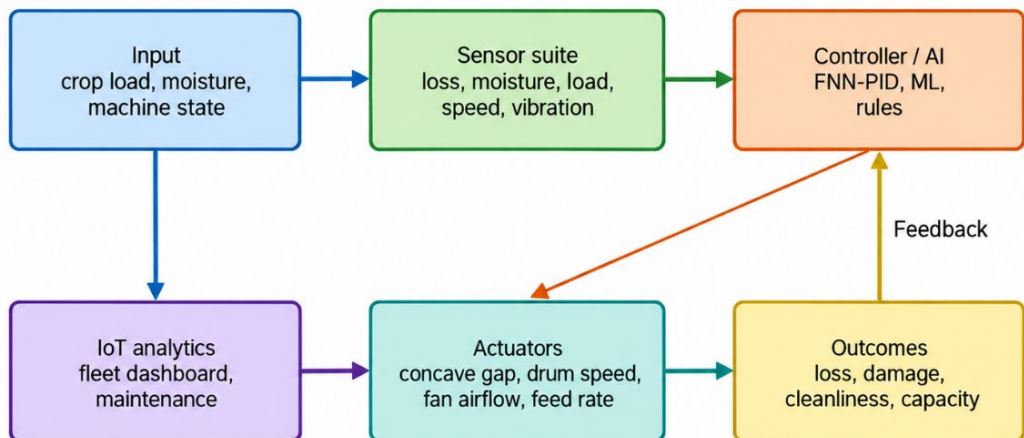


Figure 6. Conceptual architecture of a smart adaptive threshing system.

CHALLENGES AND LIMITATIONS IN ADOPTION

Modern harvesting equipment has been shown to improve farm productivity through lower labour costs, saved time, reduced crop loss after harvest. However, the rate at which this technology is being adopted, especially in the third world (smaller farms) is very slow. The largest factor contributing to the slower rate of adoption is the large upfront investment required to purchase multiple-crop or high-capacity thresher equipment (Ignatius et al., 2025). Additionally, once purchased, there will be continuous operating costs for fuel, electrical power, maintenance parts and repairs; plus an additional expense related to equipment depreciation. Credit availability for farmers with low incomes limits their ability to acquire these machines. Also, infrastructure limitations impact the potential use of these machines. Poorly maintained rural roadways create difficulties for transporting these heavy pieces of equipment. Inconsistent electricity prevents the operation of electric powered threshers. Weak fuel distribution networks limit the number of engine powered threshers that can be used. And insufficient grain storage exposes both the equipment and grain to potential damage. The lack of repair service availability and replacement parts reduce the dependability and economic viability of mechanical threshing systems (Balappa et al., 2024).

Additionally, technical and operational problems exist regarding the applicability of modern threshers to small-scale farming systems. Most modern threshers require trained personnel to set parameters (drum speed, concave clearance, air flow, feed rate) specific to each type of crop; as well as parameters based upon the crops' moisture content, straw length and grain size (Abdeen et al., 2025). Incorrect setting can lead to increased grain loss, breakage, clogging and decreased efficiency. Maintenance is a critical component of maintaining optimal performance from threshers; however most small-scale farmers have limited training and understanding of what preventative maintenance entails (lubricating bearings, adjusting belts, cleaning sieves, inspecting worn parts). Advanced technologies (sensors, internet of things (IoT), electronic controls) enhance the efficiency of threshers; however, require technical expertise that may not be available in rural communities. Smaller field sizes, seasonal production cycles, diversity in crop types, and relatively low annual yields make it unfeasible for small-scale farmers to individually own and maintain threshers (Abdeen et al., 2021). Therefore, cooperative ownership, customised hire services, training programs for farmers, access to capital markets and/or other financial support mechanisms, simple design changes in threshers, and government policy initiatives that support mechanised threshing are all important components needed to facilitate greater inclusivity, feasibility and sustainability for farmers across various levels of farm size.

EMERGING TRENDS, RESEARCH GAPS, AND FUTURE PROSPECTS

Although several review papers have thoroughly analyzed the mechanics of threshing; the effectiveness of the harvesting process; damage to grains during harvest; and loss of crops after they are harvested, most research has evaluated each aspect in isolation. Therefore, this review paper will provide an integrated overview of technology integration as it relates to advances in mechanical designs for threshers, real-time monitoring using sensors, decision making with adaptive controls, operating efficiently (in terms of

both energy usage and cost), and social economic adaptation of threshing technologies. In other words, the purpose of this review is to move away from traditional surveys of new technology and develop a structure that demonstrates how smart mechanization can take threshing systems from being static, un-sustainable, and producer unfriendly, to dynamic and adaptable post-harvest solutions

Technology readiness and commercial deployment gap

Although there are many successful demonstrations of AI assisted threshing, automated parameters for optimization, and sensor based monitoring of crop production, all of these systems are still largely in a lab setting (prototype), or field testing setting. Studies that report potential benefits of the use of these technologies to reduce grain loss, detect impurities, and adaptively control machinery; however, very little has been done regarding validating the effectiveness over multiple seasons and with varying levels of environmental stressors. The reliability of sensor based systems, which can provide real-time data such as drum speed, drum load, grain loss, moisture content, vibrations, and temperatures; will require additional study. Future research should focus on improving technology readiness through multi-season field trials, commercial-scale validation, and integration of robust control architectures.

Crop-specific adaptation gap

The scientific literature indicates that threshing performance is influenced by crop-related characteristics due to variations in both physical (grain size) and biochemical properties (attachment strength of the grain, moisture content, etc.) and also from a mechanical standpoint (mechanical resistance). Multi-crop threshers offer some degree of adaptability through adjustments to variables such as drum speed, concave clearance, and sieve openings. Research into AI-based optimization techniques have primarily been developed for single crops including but not limited to rice, maize, wheat and soybeans. Therefore, future research should be directed at developing intelligent crop identification systems that combine with adaptable algorithms which can determine optimal threshing conditions for various cereal types, legumes/pulses/oilseed products and fragile grain.

Geographical and farming-system applicability gap

The results of the evaluated study show there is an important distinction in terms of the technology used on larger commercial farms vs. smaller farm or smallholder agricultural systems. Large capacity, highly mechanized (automated) harvesting equipment including combines and threshers will be necessary for commercially farmed areas while developing countries need to have low-cost, transportable, energy efficient (e.g., solar powered) and easily maintained options. While current alternatives include solar-powered, hand-cranked, and/or very small scale threshers which could provide additional options for poor, resource-constrained farmers, integrating these with modern sensors and automation capabilities are currently limited.

Sensing capability and real-time grain quality assessment gap

The most common smart threshing system today is focused primarily upon tracking performance (operational) data and external grain quality metrics i.e., impurities in grain, cleaning performance, etc. Machine vision with deep learning has provided a detection

of contaminants and improved cleaning performance. However, the current state-of-the-art does not provide adequate real-time assessments of grain breakage/damage to internal parts of the grain and/or seed viability or quality deterioration.

Control variable and intelligent automation gap

Existing automation systems typically manage specific factors (drum speed, concave opening, air flow, and feed rate). While there has been some success with adaptive methods for controlling threshing (reducing grain loss/damage), a full range of closed loop systems capable of adjusting all operating conditions simultaneously is being developed now. In future research, we need to develop an integrated framework utilizing artificial intelligence to monitor multiple sensors and continuously adjust threshing parameters based on crop condition, equipment loading, and target grain quality.

Validation environment gap

Many studies have been conducted by scientists using controlled laboratory or short duration field tests. These test sites typically do not represent all the complexities that farmers experience due to environmental variability (weather, crop development stage, soil moisture), equipment condition (operator usage, mechanical wear) as well as differences in farm practices. Future studies will need to be directed at multi-site, long term testing across various climate/soil zones to insure reliable and scalable intelligent threshing systems.

Economic feasibility and farmer adoption gap

Although there are many positive technological advancements in using AI, IoT and automation technology, as well as potential for high start-up costs of AI, IoT and automation; cost of sensors used in these systems; power consumption by these systems (i.e., computing needs); and increased complexity of maintenance, these factors contribute greatly to why many small to mid-sized scale farms have been slow to adopt these technologies. In developing future applications, it is important to focus on creating low-cost controllers for use with AI; affordable sensors that are suitable for agriculture; energy efficient computers/hardware; and simple user interface options. Developing hybrid applications that combine elements of automated agricultural equipment with a design that would be economically feasible for small to mid-sized scale farmers could help increase access to these technologies while still provide the performance benefits that automation provides.

An important knowledge gap identified in the existing literature was the variation reported on the energy use characteristics of agricultural machinery. Many studies report various measurements such as throughputs, threshing efficiencies, cleaning efficiencies and grain losses; however, most commonly energy use is provided but may be expressed in different units or may not have been quantified at all. The consistent reporting of specific energy consumption (in terms of kWh t⁻¹ or MJ t⁻¹) combined with direct operational CO₂ emissions and life cycle environmental impact will allow for a higher degree of comparison between threshing technology options. The reporting on these factors will enable the true potential to develop environmentally friendly mechanization techniques which can balance productivity, energy requirements, cost effectiveness and environmental impacts.

Future research direction

As threshing technology evolves into the future it will be centered around making the current process (threshing) more efficient by reducing loss after harvesting crops. The ability of threshers to provide effective service regardless of type of farming being done could eventually become a reality due to advancements in technology. Modern threshers have advanced significantly through features like variable drum speeds, improvements made to the physical mechanisms of separating grains from chaff, replacement parts being available for interchange between threshers, and multi-crop threshers. However, there is still much work needed in developing an 'intelligent' method for threshing, which will include low-cost solutions for maintaining sustainability. The use of sensors, automation, and data-based methods represent opportunities for future improvements in the performance and dependability of threshing equipment.

An important area of research is developing an 'adaptive' thresher that can adjust its operating characteristics, such as drum speed, concave clearance, air flow rate, and feed rate in response to crop type and field condition. Real-time decisions made using artificial intelligence and machine learning can help improve threshing performance, reduce grain loss due to mechanical damage or other causes, and minimize energy consumed during operation.

The next generation of threshing technology is likely to focus on the application of precision agriculture concepts (such as data collection through Internet of Things [IoT] based sensors, and use of global positioning system [GPS], and data storage in the cloud) into future threshing systems. This is because these concepts can provide advantages such as; timely assessment of performance, ability to monitor equipment remotely, better operation of machinery, etc. Additionally, there is a need for additional research that focuses on developing sustainable electric, hybrid or energy assisted post-harvest processing equipment to lower the consumption of fossil fuels and minimize negative environmental impacts associated with current mechanical harvesting systems.

Additional research emphasis should include development of threshing systems which are; adaptable and cost effective for a variety of agricultural commodities and farm types, i.e., large farms, small farms, and/or small holder farms. Important to this effort will be development of: Crop specific design parameters and adjustments developed through experimental trials, User friendly control systems, and Economically feasible designs. It is anticipated that successful implementation of new threshing technologies will require an interdisciplinary approach combining advancements in technology, field evaluations, economic analyses, and consideration of farmer needs to maximize benefits.

CONCLUSIONS

Modern threshing systems now incorporate various levels of technology, and there is an increasing trend toward the use of computerised, sensor-based and digitally integrated post-harvest solutions. The development of threshing mechanisms has led to improvements in efficiency (in terms of throughput), reductions in grain loss, and greater flexibility to operate over a wider range of crops and weather conditions. While modern threshing systems provide many advances compared with traditional manual or mechanical threshers, their performance will continue to be heavily reliant upon crop characteristics, machine design and operator experience/operational decisions. Therefore, it will be essential to optimize these systems appropriately to achieve reliable operation.

Automation through the use of Internet-of-Things (IoT) based sensors, Artificial Intelligence (AI) algorithms, Machine Vision systems and Predictive Analytics enable real-time monitoring, optimization of system operation and improved decision making regarding optimal operation of the threshing system. Many reported studies demonstrate measurable advantages such as better adjustments of key parameters, lower grain loss rates, and improved machine performance. However, many studies have been performed using experimental evaluations or very limited field trials. As such, future work in this area may need to validate the results of these studies using large-scale field trials conducted in diverse agricultural settings.

Precision agriculture (PA) concepts, which include global positioning system (GPS) guidance, yield monitoring systems (YMS), telemetric and automated control systems (ACS), represent a major advance in modern threshing and combine harvesting operations. Although PA has the potential to improve yields and reduce the financial burden related to growing crops, barriers such as cost, degree of technological complexity required, maintenance requirements, and the amount of digital technology available can limit its adoption. As such, an ongoing need exists for low-cost, mobile, low-energy consuming and flexible systems that are capable of providing support for smallholder farmers while they perform their daily tasks.

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