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Review of mechanical sugarcane harvesters: Performance, efficiency and crop suitability

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Abstract

Mechanical sugarcane harvesting has become essential to modern agriculture, helping farmers overcome labour shortages while improving efficiency and productivity. The performance of these machines is influenced by several factors, including the characteristics of the crop, the terrain and how well the equipment is operated. A comparison between whole-stalk and chopper harvesters highlights key differences in throughput capacity, energy use and adaptability to different field conditions. Chopper harvesters, for example, can process up to 132.7 tonnes of sugarcane per hour under ideal conditions but tend to lose efficiency when faced with uneven terrain or more complex crop varieties. This study explores mechanical sugarcane harvesting systems' efficiency, adaptability and economic feasibility while identifying key operational and technological challenges. Advances in harvesting technology, such as precision cutting mechanisms, optimized field logistics and the breeding of sugarcane varieties designed for mechanization, have helped to improve efficiency while reducing environmental impact. However, the high cost of these machines remains a significant hurdle, especially for small-scale farmers. Making shared ownership arrangements, government subsidies and the development of cost-effective semi-mechanized alternatives are viable solutions. To fully optimize mechanical harvesting, an integrated approach is necessary. This includes leveraging technology, improving field management practices and offering specialized training programs. These efforts are essential for making sugarcane farming more sustainable, maximizing yields and ensuring long-term economic viability for farmers.

Keywords

efficiency; harvesters; mechanization; sugarcane; technology; terrain

Introduction

Mechanical sugarcane harvesters have transformed the industry by effectively addressing labour shortages and improving productivity, particularly in regions where manual harvesting is resource intensive and economically unfeasible (1). Despite these advantages, mechanical harvesters encounter challenges related to crop variability, field conditions and operational efficiency. A significant issue is that not all sugarcane varieties or terrains are conducive to mechanization (2). Varieties with larger stalk diameters or higher biomass, such as energy cane, can increase fuel consumption and mechanical wear. At the same time, uneven or irregular terrains can impair the functionality of large-scale machinery (3).

The role of mechanical harvesters is pivotal in reducing harvesting duration, lowering labour expenses and expanding operational capacity, making them indispensable for large-scale sugarcane plantations (4). However, their performance is influenced by a combination of factors, including the crop's mechanical properties, such as stalk length, diameter and density, field topography and climatic conditions (5). Mechanical harvesters may face operational difficulties in sloped or waterlogged areas, necessitating modifications like smaller, more adaptable machinery for such challenging environments (6). To enhance efficiency and applicability, mechanical harvesters must be designed to align with specific crop characteristics, field dimensions and local environmental conditions. Key performance optimization areas include cutting precision, fuel efficiency and material throughput, ensuring that these machines meet the diverse operational demands of sugarcane producers globally (7, 8).

Harvesting Techniques

Sugarcane harvesting methods fall into two main types: manual and mechanical. Mechanical harvesting can involve whole-stalk machines through linear or transverse windrowing or chopper harvesters that cut the cane into smaller pieces to make transport and processing easier (9, 10).

Whole stalk harvesting

This harvesting method is predominantly utilized in Southern Africa and certain parts of the USA. Whole-stalk harvesters are engineered to collect intact sugarcane stalks, which can be stored or processed without rapid degradation, making them highly suitable for fields with upright sugarcane stands (11). This approach minimizes mechanical damage to the crop, thereby preserving stalk integrity. However, the system reduces efficiency in challenging terrains, particularly on steep slopes or when crops are lodged. For instance, while these machines have demonstrated high performance in South African sugarcane plantations, they are less effective in fields not explicitly configured for mechanized harvesting (3, 12).

Chopper harvesting

Primarily employed in large-scale operations in regions such as Australia, Brazil and parts of the USA, chopper harvesters cut sugarcane into billets during harvesting. This method is highly efficient for optimizing transportation and storage logistics, although it necessitates immediate processing to prevent degradation of sugar quality. Studies conducted in Egypt indicate that chopper harvesters are the predominant choice in fully mechanized systems, particularly in fields with sprawled or lodged cane, where they perform better than whole stalk harvesters (10, 13). Table 1 compares chopper and whole stalk harvesters by capacity, crop suitability, fuel use and advantages. Chopper harvesters handle sprawled cane with high throughput, while whole stalk harvesters suit upright cane and preserve stalk quality (14, 15).

Table 1. Comparison of chopper and whole stalk harvesters: performance, suitability and fuel consumption

Harvester type	Capacity (t/hr)	Crop suitability	Fuel consumption (l/hr)	Advantages
Chopper Harvester	132.7 (14)	sprawled cane (10)	18 (10)	High throughput, ideal for large fields (14)
Whole Stalk Harvester	100 (15)	upright cane (15)	15 (8)	Less crop damage retains stalk integrity (15)

Harvester Performance Metrics

Key performance metrics for assessing harvester efficiency include harvesting speed, material throughput and energy consumption. Notably, harvesting and loading represent the most significant costs in sugarcane production, comprising 35 % of total production expenses. The expenses exceed land preparation, planting and weeding (16). Row length is also a crucial determinant of performance, with optimal efficiency typically achieved when rows are between 500 and 700 m long (5).

Due to the higher bulk density and biomass of energy cane, chopper harvesters require up to 1.65 times more power to process energy cane than conventional sugarcane. While chopper harvesters achieve a throughput rate of 132.7 tons per hour for sugarcane, the rate drops to 43.3 t/hr for energy cane, underscoring their greater adaptability to traditional sugarcane harvesting (14). Under optimal conditions in Brazil, throughput rates of up to 44 t/hr have been recorded, significantly enhancing operational efficiency (17).

Serrated edge blade designs have proven highly effective in minimizing crop damage, reducing sap leakage and lowering spoilage (10). Stalk diameter and cutting speed significantly influence harvester performance. Larger stalks demand more cutting force, reducing productivity at higher speeds, whereas smaller stalks facilitate more efficient cutting, thereby increasing productivity. The highest cutting efficiency (100 %) was observed for stalks with a diameter of 1.38 cm, while larger stalks, up to 3.28 cm, showed a slightly lower efficiency of 83.67 % (8).

Sugarcane varieties with a Poisson's ratio of 0.404, an elastic modulus of 92 MPa and a density of 1145 kg/m^3 demonstrated optimal cutting performance with minimal structural damage. Increased elastic modulus led to higher cutting stress, while lower densities contributed to inconsistent cutting results. Moreover, single-row planting with 1.4 m spacing improved cutting quality and regrowth compared to double-row planting configurations (18).

Efficiency of Mechanized Harvesting

Manual harvesting, which has dominated the sugarcane industry for decades, is labour-intensive and incurs significant costs in terms of person hours. In contrast, mechanized systems have demonstrated the ability to reduce labour demands by 60-70 % in field evaluations (19). In Pakistan, a locally developed whole stalk sugarcane harvester achieved a field efficiency of 75.10 % and a material handling capacity of 12.87 tons per hour under optimal conditions. The harvester's efficiency increased with higher gear settings, elevated engine speeds and broader working widths, enhancing field capacity (9). Additionally, specific energy consumption decreased at higher forward speeds, improving energy efficiency (10).

By employing a multi-objective particle swarm optimization model, they reduced time spent on manoeuvring, significantly boosting overall productivity (20). Furthermore, advanced quality monitoring systems, such as spectroscopic methods, enable farmers to make data-driven decisions regarding harvest timing, optimizing sugar content and minimizing losses (21). Sugarcane varieties with higher elastic modulus tend to resist cutting, leading to greater power consumption and accelerated wear on harvester blades. Conversely, varieties with lower modulus, such as Liucheng 05-136, allow for cleaner cuts and reduce plant damage, making them more suited for mechanized harvesting (18). The environmental advantages of mechanical harvesting, particularly in reducing greenhouse gas emissions associated with cane burning, further underscore its potential for future adoption (1).

Economic Impact of Mechanized Harvesting

The cost comparison between mechanization and manual labour concludes that mechanized operations can reduce costs by up to 45.91 % (4). However, the transition to mechanized harvesting has been slow, primarily due to insufficient infrastructure to support large-scale mechanized operations (22). In India, high-end machinery can cost up to 1.2 crore INR, rendering them inaccessible to small-holding farmers. To address this, semi-mechanized systems are being developed, offering smaller, more affordable machines that lower labour costs while maintaining reasonable efficiency (23).

The impact of chopper harvesters on operational costs emphasizes optimizing these machines to balance energy efficiency with cost-effectiveness. Improper optimization could lead to increased operational expenses. The optimized harvesting routes and machine operations resulted in fuel consumption reductions of over 30 %, significantly improving operational savings (24). Proper management of trash blankets also plays a crucial role in enhancing harvesting efficiency and promoting soil health by retaining moisture and nutrients. However, excessive trash layers can obstruct harvester blades, leading to higher fuel consumption (25). Table 2 summarizes three sugarcane harvesting methods, comparing their efficiency, labour requirements, costs and greenhouse gas emissions, highlighting that fully mechanical harvesting offers the most benefits in terms of efficiency, reduced labour and lower environmental impact.

Factors Affecting the Suitability of Mechanical Sugarcane Harvesters

The effectiveness of mechanical sugarcane harvesters depends on several factors: crop characteristics, terrain challenges and climate and field conditions. Crop type (upright vs. sprawled) significantly affects harvester suitability, while rough or uneven terrain introduces operational challenges. Furthermore, climate and field conditions influence harvester performance and efficiency, ultimately guiding the selection of appropriate machinery for optimal results. These factors are discussed below.

Impact of crop characteristics on harvester suitability

Harvesters are typically engineered with specific crop varieties in mind and their performance can vary depending on the region. The length and diameter of sugarcane stalks are critical factors that impact the efficiency of cutting and handling during mechanical harvesting. Machines that accommodate various stalk sizes are more versatile and suitable for multiple crop types (26). In Egypt, whole stalk and chopper harvesters are employed depending on the crop's readiness for processing. Energy cane, a relatively new bioenergy crop, presents challenges due to its higher stem density. This necessitates modifications to standard sugarcane harvesters to manage the increased biomass effectively and minimize spillage (3).

Challenges of Terrain for Mechanized Harvesting

Terrain plays a crucial role in determining the suitability of harvesters. In hilly regions, large machines tend to perform poorly, as steep slopes and small field sizes hinder their operational efficiency (Fig. 1) (22). In South Africa, mechanized harvesters face difficulties on steep slopes or when processing recumbent sugarcane. Conversely, countries like Australia and the USA, with expansive, flat fields, are ideal for large-scale chopper harvesters, which can efficiently process substantial quantities of sugarcane without requiring extensive field preparation (3, 17).

In more challenging terrains, such as sloped areas, smaller, more flexible machines equipped with real-time monitoring systems have enhanced the adaptability of harvesters. The use of smaller, adaptable machines in these regions to improve the effectiveness and suitability of mechanized harvesting (7). The graph compares the performance of manual, semi-mechanized and fully mechanized harvesters on flat, slightly sloped and hilly terrains. Performance declines as terrain difficulty increases, with fully mechanized harvesters showing the highest efficiency across all terrains, followed by semi-mechanized and manual methods.

Influence of Climate and Field Conditions on Harvester Performance

Climatic conditions are a critical factor influencing harvester performance. In Okinawa, Japan, small crawler-type harvesters have demonstrated superior effectiveness in wet conditions compared to larger, wheel-based machines. The importance of developing small-scale harvesters specifically designed to accommodate the unique soil and climate conditions in regions like India, where local environmental factors differ considerably from those in more mechanized agricultural systems (23).

Table 2. Comparison of harvesting methods: Efficiency, labor requirement, cost and environmental impact

Harvesting methods	Efficiency (%)	Labor (hr/ha)	Cost (USD/ha)	GHG emissions (tons CO_2 e/ha)
Manual (Burnt Cane)	75 % (1)	40 (4)	150 (4)	High (1)
Semi-Mechanical	85 % (9)	15 (9)	100 (9)	Medium (9)
Fully Mechanical	90 % (10)	5 (10)	80 (10)	Low (1)

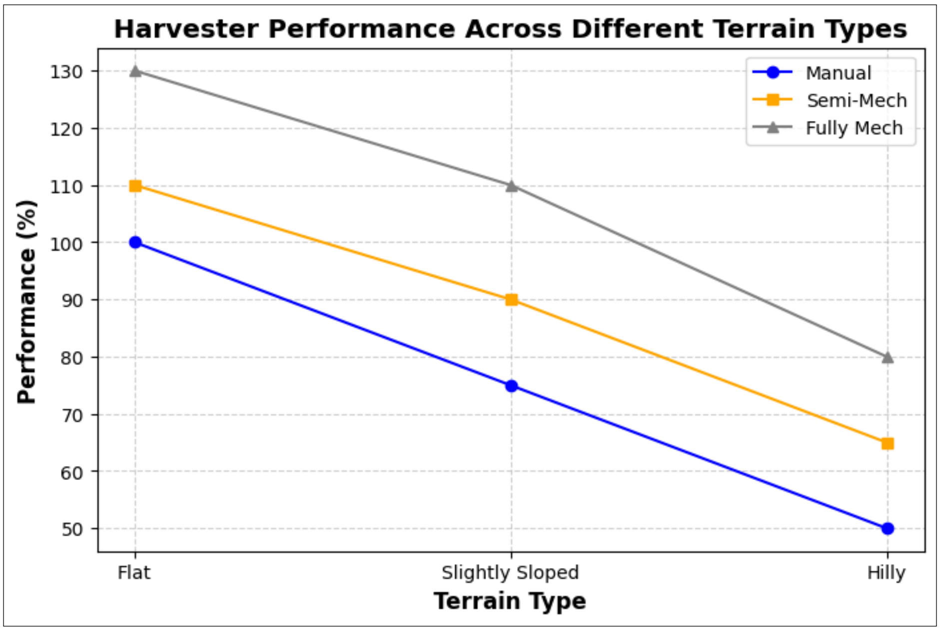

Fig. 1. Line diagram of impact of terrain on harvester performance efficiency (6).

Conclusion

Mechanical sugarcane harvesters offer substantial benefits regarding labour savings and productivity, though several factors heavily influence their performance and efficiency. The size and flexibility of a crop's stalk can significantly affect how efficiently it's cut and how much damage is avoided during harvesting. At the same time, rough or hilly terrain can be a real challenge for large machines, making it clear that smaller, more adaptable harvesters are needed to handle these tricky conditions.

Addressing these challenges requires the development of sugarcane varieties suited explicitly for mechanical harvesting, as well as the adoption of machinery designed to handle diverse field conditions. While mechanization reduces costs over time, the high initial investment remains a significant barrier for small-scale farmers. Semi-mechanized systems and government subsidies could help bridge this gap, facilitating broader access to these technologies. In conclusion, advancing mechanical harvesters through improvements in crop selection, technology and support systems is critical to boosting efficiency and making mechanization more sustainable and accessible to a broader range of farmers.

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Authors' contributions

ML carried out the literature collection and drafted the manuscript. KP made revisions and participated in the manuscript design and final draft making. TS made revisions and participated in the manuscript design and final draft making. TR made revisions and participated in the manuscript design and final draft making. SS made revisions and participated in the manuscript design and final draft making. KM made revisions and participated in the manuscript design and final draft making.

All authors read and approved the final manuscript.

Compliance with ethical standards

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