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Advancements of agriculture 4.0 in mechanized sugarcane harvesting: a review

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ABSTRACT: This study reviewed the advancements of Agriculture 4.0 in mechanized sugarcane harvesting, analyzing the efficiency of the mechanized harvesting system and evaluating the impact of the harvesting, loading, and transportation process costs. The mechanized sugarcane harvesting system in the 2020/21 harvest reached 91.6% or approximately 588 Mg in Brazil. As this activity demands a high amount of capital - assets, labor, inputs - the cost of the harvesting, loading, and transporting process represents 40% of the sugarcane production cost. The continuous delivery of raw material to the industrial processing unit is essential to ensure stability and maximum yield for obtaining sugar and ethanol, especially in an environment with geographical dispersion of harvesting fronts and agronomic factors linked to crop management. Therefore, tools that enable real-time equipment tracking benefit process management. Digital agriculture, defined as the application of technologies that seek to add intelligence and process automation, allows for improved agricultural management of farms, making it possible to reach new productivity levels in the field. The data generated through digital agriculture allows for the creation of models to construct scenarios that improve decision-making, both in terms of operational strategies - distribution of resources by harvesting front - and long-term strategies - the adoption of new technologies in the process.
Key words: mechanization, digital agriculture, modeling, technology.

Avanços da agricultura 4.0 na colheita mecanizada de cana-de-açúcar: uma revisão

RESUMO: O objetivo deste estudo foi revisar os avanços da Agricultura 4.0 na colheita mecanizada de cana-de-açúcar, analisando a eficiência do sistema de colheita mecanizada e avaliando o impacto dos custos do processo de colheita, carregamento e transporte. O sistema de colheita mecanizada de cana-de-açúcar na safra 2020/21 alcançou 91,6% ou aproximadamente 588 Mg no Brasil. Como essa atividade demanda uma grande quantidade de capital - ativos, mão de obra, insumos - o custo do processo de colheita, carregamento e transporte representa 40% do custo de produção de cana-de-açúcar. A entrega contínua de matéria-prima à unidade de processamento industrial é essencial para garantir estabilidade e rendimento máximo na obtenção de açúcar e etanol, especialmente em um ambiente com dispersão geográfica de frentes de colheita e fatores agronômicos ligados ao manejo da cultura. Portanto, ferramentas que permitem rastreamento em tempo real dos equipamentos beneficiam o gerenciamento do processo. A agricultura digital, definida como a aplicação de tecnologias que buscam adicionar inteligência e automação de processos, permite melhorar o manejo agrícola das fazendas, possibilitando alcançar novos níveis de produtividade no campo. Os dados gerados por meio da agricultura digital permitem a criação de modelos para construir cenários que melhorem a tomada de decisões, tanto em termos de estratégias operacionais - distribuição de recursos por frente de colheita - quanto em estratégias de longo prazo - a adoção de novas tecnologias no processo.
Palavras-chave: mecanização, agricultura digital, modelagem, tecnologia.

INTRODUCTION

Brazil has witnessed significant advancements in the mechanized harvesting system, particularly in the sugarcane sector. The percentage of mechanized harvesting has seen remarkable growth, from 37.1% in the 2008/9 harvest to an estimated 91.6% in the 2020/21 harvest. This progress is particularly notable in the Center-South region, where the relief favors mechanization, with a current mechanization rate of 97.8%. São Paulo, responsible for approximately 50.3% of the harvested area in the current harvest, has also experienced a substantial increase, with the mechanized harvest index rising from 47.6% in the 2008/9 harvest to 98.6% in the 2020/21 harvest.

The shift towards mechanization, without prior burning of sugarcane fields, not only reduces greenhouse gas emissions but also benefits soil health. The practice of leaving the straw on the soil, which was previously burned, helps protect against erosion and contributes to increased fertility and organic matter content (CONAB, 2020).

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Accurate information on production costs is crucial for effective agricultural management. It plays a vital role in analyzing the efficiency of production activities and in studying specific production processes, ultimately determining the success of agricultural companies. The importance of production cost analysis has grown significantly in rural administration and business planning. Fortunately, advances in information technology have made it easier to estimate these costs, as agricultural companies increasingly adopt digital tools for data recording (DA SILVEIRA et al., 2021; IPEA, 2016; ZHAI et al., 2020).

To sustain the expansion of national agro-industrial production through productivity gains and cost reductions, the agriculture sector is transitioning to Agriculture 4.0. This new phase integrates new information and communication technologies, such as the Internet of Things (IoT), artificial intelligence, analytics, big data, as well as sensing and traceability devices. This transition is essential for optimizing resource use, such as water and energy, and driving further advancements in the agricultural sector (ARAÚJO et al., 2021; DA SILVEIRA et al., 2021; KLERKX et al., 2019; LIU et al., 2020; MILANEZ et al., 2020; SEMIONATO et al., 2020; ZHAI et al., 2020).

DEVELOPMENT

Planning and costs in mechanized sugarcane harvesting

Mechanization is crucial in harvesting and transport operations from field to industry due to a large amount of biomass that needs to be handled. Planning the use of resources used in harvesting, loading, and transporting requires decisions that are not limited to their quantification. Aspects related to the management of harvesting fronts and management aspects must be considered. Therefore, operations planning must occur in a coordinated manner and a systemic view since a decision on an issue entails direct interference in the entire system, given the strong interaction between the resources involved (BRAUNBECK & MAGALHÃES, 2014).

The Harvesting, Loading, and Transport process are responsible for around 40% of the sugarcane production cost. This part of the raw material cost formation is due to the great need for equipment and people involved in this stage of the production chain, therefore having a tool that allows sensing of components, the geographic position of equipment in real-time, visualization of the operation path harvesting, automatic notes and man-machine interface that allow for more excellent equipment performance is essential for establishing a management model that aims to reduce costs (BANCHI et al., 2019; CORRÊDO et al., 2021; MILANEZ et al., 2020).

Digital agriculture or Agricultue 4.0

Digital technologies are being used in the most diverse areas, seeking to cover as many systems and realities as possible, with a common goal of accelerating and optimizing the use of resources used to produce more with less (ALBIERO et al., 2020; DA SILVEIRA et al., 2021; LIMA et al., 2020; MEGETO et al., 2020; SEMIONATO et al., 2020). In this ideal, there is a need to create digital solutions for food production, which is one of the significant challenges of the 21st century, where the world population grows exponentially, and productivity in the agribusiness sectors has the task of keeping up with this growth sustainable. Therefore, through the development of technologies and the need for solutions, tools were created to enrich the use of information in the field and help rural producers make decisions through accurate data analysis (VILLAFUERTE et al., 2018; ZHAI et al., 2020).

Digital agriculture refers to the insertion of information technologies and applications in agriculture, which together seek to add intelligence to devices, sensors, and equipment, automating agricultural operations, rationalizing the use of inputs, and improving the agricultural management of farms, making it possible to achieve new levels of productivity in the field (ALBIERO et al., 2020; KLERKX et al., 2019; LIU et al., 2020; VILLAFUERTE et al., 2018; GARCIA et al., 2022).

Connectivity, monitoring, and automation are essential elements for managing activities. In addition, the use of managerial, financial, and accounting information corroborates the achievement of results for decision-making, improving stock returns, and controlling the financial resources involved in the operation (LANÇONI et al., 2020; ZHAI et al., 2020).

Agriculture 4.0 was developed based on the precepts of precision agriculture, to which new technologies were added, always with the central premise to enable greater connectivity to capture field data and generate useful information for the producer. In this sense, new computational technologies such as the Internet of Things (IoT), Big Data, Cloud Computing, Machine Learning, an area of study in the field of artificial intelligence, have expanded the range of possibilities to make agriculture intelligent and increasingly competitive (ALBIERO et al., 2020; MEGETO et al., 2020; LIMA et al., 2020; SEMIONATO et al., 2020; VILLAFUERTE et al., 2018).

The internet of things combines several complementary technologies that enable the integration of objects from the physical environment to the virtual world. This technology can provide various services, such as temperature monitoring, geographic coordinates, data aggregation, collaboration, and intelligence, making it possible to manage operations hundreds of kilometers away, track assets that cross the ocean, or detect pests or diseases in the plantation. Furthermore, the IoT redefines the information sharing process, whereas before, the information was shared between people through information systems, now the information is shared between machines, which connect and, from this information exchange, perform intelligent actions (ALBIERO et al., 2020; DA SILVEIRA et al., 2021; LIU et al., 2020; VILLAFUERTE et al., 2018).

There are four main axes of the impact of the use of IoT applications in rural activities: (i) productivity and efficiency; (ii) equipment management; (iii) asset/animal management; and (iv) human productivity (MILANEZ et al., 2020). Concerning the first item, sensors and drones can be used for meteorological and soil monitoring, controlling humidity, ambient temperature, nutrients, and water consumption. The planted area can be monitored to identify pests and fungi, ensuring their quick correction. The individual monitoring of each stand allows evaluating the suitability of the soil for each crop and optimizing planting (GARCIA et al., 2022).

Another relevant source of use of IoT applications is in equipment management, logistics, and storage. It is possible to define planting and harvesting routes that maximize physical productivity. Embedded sensors collect data from the machines, analyze them (“analytics”), and allow preventive maintenance and parts replacement, thus avoiding unexpected breakdowns. Management also improves fuel consumption, reducing carbon dioxide (CO2) emissions and generating environmental benefits. There are still gains arising from the movement of the harvest between the place of production and the places of destination through the definition of times, modes of transport, and use of warehouses to reduce production losses and minimize costs (KLERKX et al., 2019; ZHAI et al., 2020; GARCIA et al., 2022). Sugarcane harvesters have a high level of embedded technology, which generate data in real-time and assist in monitoring parameters related to the harvesting operation (CORRÊDO et al., 2021).

Agricultural automation uses a set of tools that accelerate learning and is easily assimilated by employees who work in production processes. Agricultural automation enables real-time monitoring of the operation, sustainably ensuring maximum productivity at the lowest cost, as shown in figure 1.

The focus of monitoring agricultural assets is always seeking to increase operational efficiency through understanding the reasons for stopping and, from there, generate action plans to minimize these unproductive events and; consequently, reduce costs (DA SILVEIRA et al., 2021; DIAS NETO, 2021).

The approach to the automation and management solution consists of installing on-board computers, including telemetry, of managing the machines involved in the process of cutting, loading, and transporting the sugarcane that provides a management system for mobile assets and processes suited to the operational reality of the sugarcane industry’s production units (MANZONI, 2015).

An onboard computer is an embedded device, that is, installed inside a piece of equipment, which performs two types of functions: recording the equipment’s vital signs, and allow the recording of notes by the equipment operator. To ensure that the expected results are obtained, it is essential that the equipment involved in agricultural automation to be used present the following characteristics: reliability and robustness, flexibility, and extensibility, offering a comprehensive and configurable solution for different types of equipment - harvesters, truck, tractors, light vehicles, motor pump - integration with precision agriculture devices, status identification according to ongoing operation: productive, unproductive, maneuvering and capturing production data and productivity maps. The interface between operator and automation equipment is a critical factor that must be considered. The main attributes are allowing consistency in data entry, monitoring equipment performance by the operator, alarms and operational indications, and generating geo-referenced notes. Another aspect to be considered refers to the transmission of data captured from sensors – telemetry. The captured data will be sent through the communication infrastructure, segregated into two types: critical and non-critical. Critical data will be sent over the GPRS or satellite channel, in that order, and non-critical data will be sent over the Wi-Fi network established between the field assets and taken to the bioenergy unit by self-propelled vehicles that perform the field-plant logistic cycle often not more than 3 hours. This functionality is essential for: Monitoring the route, position, and status of assets ahead; Positioning of assets in the

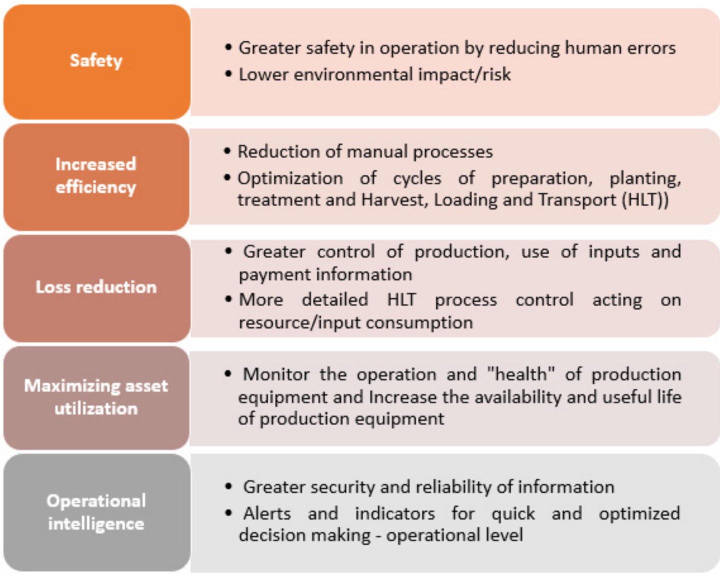

Figure 1 - Advantages of automation in agriculture and improvements in its applications. Source: Dias Neto (2015).

field: at defined intervals and by event – productive and unproductive operations; Equipment status: at a defined interval and by event (stop); For the operator: real-time - with limit violation alarm and automatic registration of violations; Validation of Service Order in use - online; Maximize asset efficiency; Indication of the reason for the stoppage and sending the active status of the equipment - Productive/Unproductive; Automatic record of breaks; Increase the reliability of notes; Consistency of information. The onboard computer is an embedded microcomputer connected to the equipment. Its programs and algorithms process data collected through sensors connected to components of agricultural machines that interpret their operational states (working or in a stopped state). This equipment can be programmed to receive notes, which agricultural machinery operators can make. All these processed data can be sent at different signal levels, such as GPRS (General Packet Radio Services or General Packet Radio Services), which enables data transmission. There is also the possibility of creating autonomous data transmission systems made available by some technology companies. Another aspect is that the installation of the GNSS antenna recognizes the location of the equipment. All this technology is incorporated into the onboard computer, enabling data generation from the entire machine in its operational form and as its location anywhere in the field (ARAÚJO et al., 2021; DA SILVEIRA et al., 2021; DIAS NETO, 2021; LIMA et al., 2020; GARCIA et al., 2022).

Onboard computers allow direct operation management by the machine operator, with important information about the operation in local memory in the machine's computer, such as superior speed and RPM by type of operation or in a function of the productivity or TCH (Ton of Sugarcane per Hectare) of the area (MANZONI, 2015). These visual management features for the machine operator allow actual field savings of up to 15% of sugarcane harvesters' diesel consumption. The installation of onboard computers in agricultural machines allows obtaining data related to telemetry (records of vital signs of the equipment), mainly with data obtained through reading by induction of the CAN Network (Controller Area Network or Control Area Network) and the notes of operations by the operator, generating a large amount of data from agricultural operations, all in real-time. Through an appropriate interface in the onboard computers, the operator and monitoring his performance through visual management can make notes to close operational costs at the end of the work shift. For machines that require visible management by the operators and operational notes, with high maintenance costs and diesel consumption, there is a need for an interface with fast and intuitive dashboards for decision-making by the operator, such as the onboard computer interfaces for sugarcane harvesters (Figure 2).

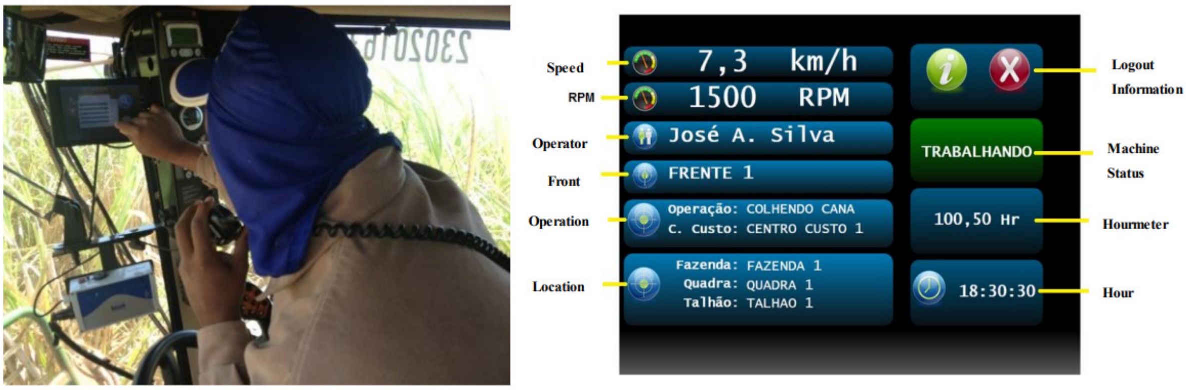

Figure 2 - Worker using the onboard management interface via onboard computer and screen of this interface with information such as speed, rotation, machine's working status, among others. Source: MANZONI (2015).

Equipment that does not require detailed visual management, but requires operational notes, uses an interface without the dashboard function, such as computers for tractors, self-propelled sprayers, and fertigation spools (MANZONI, 2015).

The hybrid communication of the on-board computer communication modules allows switching between satellite, GPRS/3G, VHF radio, Wi-fi 802.11b or ZigBee channels, with an embedded business rule for using the channels, depending on the cost of the bandwidth by the technology used and type of information to be transferred. The data transmitted from the telemetry component use, exclusively, long-range communication means: satellite and GPRS/3G, and is data from engine sensors and machine situation, considered critical, while the data transmitted by communication networks between machines and short-range: VHF radio, Wi-fi, and Zigbee are data from mechanized appointment bulletins and sugarcane entry bulletins (MANZONI, 2015).

Telemetry means the art of measuring things. The term is used as a technology that allows remote measurement and communication of information between systems through wireless communication devices such as radio waves or satellite signals within the industry. The reliability of communication and quality assurance of the data generated via sensors and on-board geoprocessing, replacing traditional field records is genuine with good agricultural automation, allowing automatic integration of mechanized report cards and the Electronic Sugarcane Certificate with Agricultural ERP (MANZONI, 2015; ZHAI et al., 2020; GARCIA et al., 2022).

In addition to ERP integration, automation must be integrated with expert decision-making systems, such as control and decision-making modules for dispatching sugarcane transport trucks to the fronts and fleet maintenance control modules, giving greater assertiveness to these powerful tools for logistical control and maintenance of the fleet, which are the basis for adequate and efficient fleet management.

With increased assertiveness in the dispatch of trucks to the fronts by specialist software, it is possible to execute and guarantee precision to the micro logistics of the harvesting fronts through the automation of the dispatch of transshipments, depending about the machines and the availability of load on the fronts.

Automated process management system (APMS) and performance of harvester

Geographical intelligence platforms, in which they analyze a large volume of georeferenced data, converting them into performance indicators capable of organizing them into support panels, help the technician's decision making (VILLAFUERTE et al., 2018).

The APMS is a system for managing activities and direct communication with all equipment with the Solinftec® on-board computer. This system makes it possible to carry out various types of registrations, monitor all processes in real-time, and querying all occurrences through system reports. In monitoring, there are several functions, such as information statistics (technical and operational) of equipment, informational alarms of problems or warnings defined by rule; it is possible to generate traces of the routes taken by the equipment, and even send messages and online commands to the on-board computer, so that information can be sent to the driver and have better results when managing the company's work system. The system has the characteristic of being web. That is, it can be accessed from any terminal that has internet communication and by any internet browser (DIAS NETO, 2021).

DIAS NETO et al. (2022) during a performance test with CH670 John Deere and Case A8810 harvesters in alternating double spacing of 0.9m x 1.40m obtained data regard times and movements from the SPGPA® platform associated with embedded technology and it was concluded that there is room for improvement in operational management, such as unproductive hours and logistical times. The analysis of logistical times shows the importance of operational procedures for end-of-line maneuvers in the mechanized harvesting operation. When analyzing unproductive hours, the most significant impact was the error in dimensioning the overflows necessary for the harvester to obtain better operational results. Indeterminate hours are due to communication/data transmission failure.

Embedded technology associated with platforms that enable the compilation of data provides information that allows creating an analysis model that supports the management of the Harvesting, Loading and Transport process and the proposal for the analysis and management of the cutting, transshipment, and transport process is structured to define sugarcane harvesting process. The equations obtained are helpful in defining operational and costs parameters and are the basis for defining sizing. Follow-up of operations through agricultural automation results in the implementation of a management routine based on indicators (DIAS NETO et al., 2022).

In operational research to define operational harvesting capacity, BANCHI et al. (2020) conclude that agricultural productivity is directly proportional to operational harvesting capacity but not linear due to mechanical limitations of the equipment. The proposed model by DIAS NETO et al. (2022) also allows cost comparison for mechanized harvesting as a function of spacing, TCH variation and number of lines harvested simultaneously (Figure 3).

BANCHI et al. (2019) pointed out for a single-row harvester at a spacing of 1.50 m, having as variables agricultural productivity and the operational life of the harvester values from 26.43 to 7.23 R$ t^{-1} , indicating that the cost of harvesting decreases non-linearly as a function of increased productivity. It is important to note that operational parameters such as the end of line maneuvering time (TM) and shot length (CT) has a significant impact on operating income and consequently on costs – (Figure 4).

The mechanized harvesting system is a substantial cost component in the sugarcane agroindustry, corresponding to about 40% of the raw material cost (DIAS NETO, 2015), thus justifying the detailed analysis of the cost composition (Figure 5). In the scenario addressed, costs Fixed assets represent 50% of the total cost, indicating that the correct sizing of equipment, given its high acquisition cost, and employees is essential for cost control.

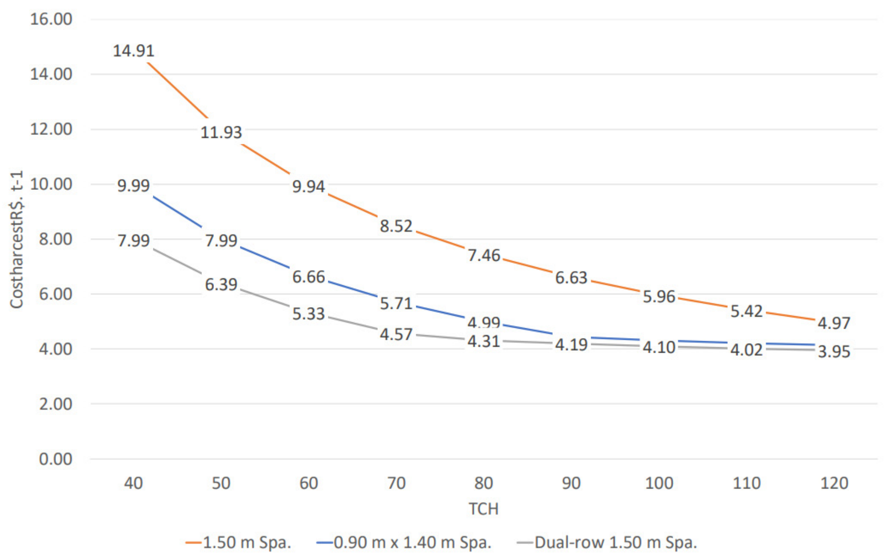

Figure 3 - Cost comparison in mechanized sugarcane harvesting, involving spacings of 1.50 m and 0.90 m x 1.40 m, as well as harvesting of two simultaneous rows in a spacing of 1.50 m.

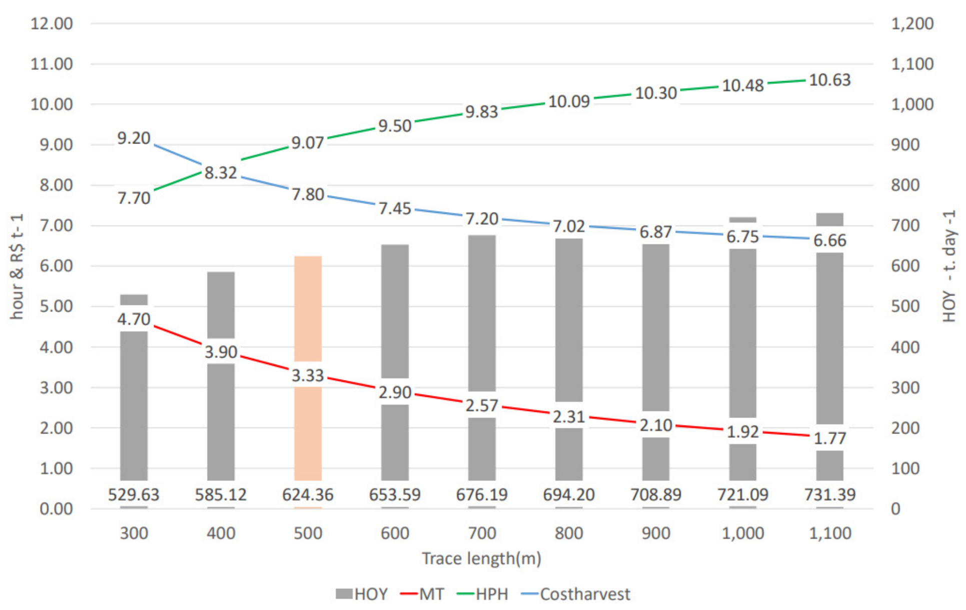

Figure 4 - Effect of cutting length on the operational performance of a sugarcane harvester at a 1.50 m spacing, considering different cutting length configurations. ROC: harvester operating income; TM: end of line maneuver; HPC: productive harvester hours and Cost: cost of mechanized harvesting R$ t^{-1}.

CONCLUSION

The advancements of Agriculture 4.0 in mechanized sugarcane harvesting have been significant, with the 2020/21 harvest reaching high levels of mechanization in Brazil. The analysis of the efficiency of the mechanized harvesting system and the evaluation of the process costs highlighted the importance of continuous delivery of raw material to the processing unit to ensure stability and maximum yield in sugar and ethanol production. The use of real-time tracking tools and the adoption of digital agriculture have enhanced process management, allowing for the creation of models that improve operational and strategic decision-making. These advancements not only enhance production efficiency but also contribute to the sustainability and competitiveness of the agricultural sector.

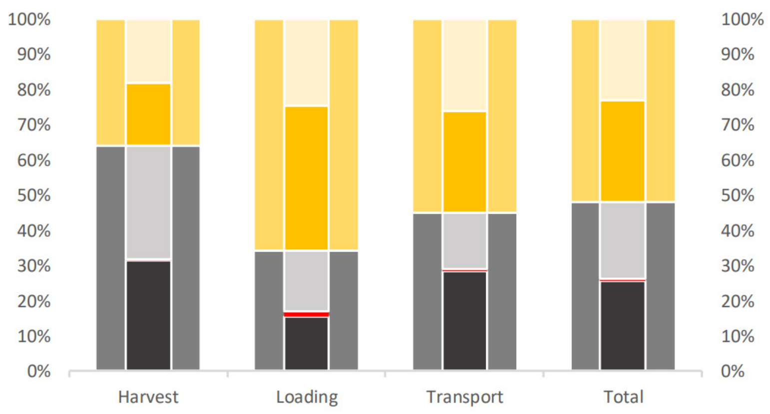

Figure 5 - Percentage distribution of costs in mechanized harvesting system operations.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

All authors contributed equally for the conception and writing of the manuscript. All authors critically revised the manuscript and approved of the final version.

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