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DANIEL SCHMIDT

# DIGITAL TRANSFORMATION IN ENGINEERING SOLUTIONS FOR POST-HARVEST GRAIN HANDLING: OPPORTUNITIES AND CHALLENGES

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DANIEL SCHMIDT

# DIGITAL TRANSFORMATION IN ENGINEERING SOLUTIONS FOR POST-HARVEST GRAIN HANDLING: OPPORTUNITIES AND CHALLENGES

Dissertation presented as a partial requirement to obtain the title of Master’s in Production Engineering and Systems, by the Graduate Program in Production Engineering and Systems of the University of Vale do Rio dos Sinos – UNISINOS

Advisor: Prof. Dr. Miguel Afonso Sellitto

Co-advisor: Prof. Dr. Enzo Morosini Frazzon *(UFSC - Federal University of Santa Catarina)*

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Approved on September 25, 2024.

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*I dedicate this dissertation to my parents Lotário Schmidt and Heidi Schmidt, and to my uncles Anneliese Bender-Mix and Friedemann Karl Hermann Mix (in memoriam). They have always encouraged me in my studies, and I consider them as examples in life.*

*"Time does not stand still; we move forward together, and in the future, we will be the past."*
*Lotário Schmidt*

*“The human mind is part of the infinite intellect of God.”*
*Espinoza*

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# ABSTRACT

This dissertation analyzes digital transformation in the post-harvest grain sector, emphasizing the adoption of digital technologies, their associated opportunities, challenges, and economic and operational impacts. The research includes a bibliometric analysis of emerging technological trends, two case studies involving a Brazilian engineering solutions company, and an empirical investigation conducted at an international research institute in Germany. The dissertation comprises three significant articles. The first article employs bibliometric analysis to identify key global research trends related to digital transformation in post-harvest operations. The second article explores the opportunities that digitalization presents for an engineering solutions provider. The third article provides a comprehensive analysis of the impacts of digital transformation on the company's efficiency, competitiveness, and operational results, utilizing data from the empirical investigation. The findings underscore the importance of digital technologies - such as automation systems, artificial intelligence, and sensors - illustrating their positive effects in 9 distinct areas within storage units, where notable losses occur. The research indicates that these technologies can reduce grain losses by up to 7%, enhancing overall process efficiency. The adoption of these innovations contributes to reducing energy consumption, improving quality control of grains, and increasing food safety. In the drying process, the identified innovations suggest potential operational gains estimated at USD 700 million annually in Brazil. The dissertation analyzes the strategy adopted by a company during the digital transformation process, demonstrating the capacity of these innovations to generate both quantitative and qualitative economic value, benefiting not only the post-harvest sector but also the entire agricultural supply chain. This research offers valuable insights for companies and researchers interested in exploring digitalization opportunities in the post-harvest grain sector, emphasizing the achievable economic and efficiency gains.

Keywords: Digital transformation. Post-harvest. Agriculture. Efficiency. Innovation. Strategy. Digital technologies.

## LIST OF FIGURES

## ACRONYMS LIST

| | |
|---|---|
| CONAB | National Supply Company |
| ONU | United Nations Organization |
| FAO | Food and Agriculture Organization of the United Nations |
| PIB | Gross Domestic Product |
| KEPL3 | Publicly traded company on the stock exchange |
| BI | Billions |
| MM | Millions |
| BIBA | Bremer Institut für Produktion und Logistik GmbH |
| Uni-Bremen | University of Bremen |
| LogDynamics | Bremen Research Cluster for Dynamics in Logistics |
| Lab | Laboratory |
| EMBRAPA | Brazilian Agricultural Research Corporation |
| FSC | Food Supply Chain |
| CCP | Critical Control Points |
| GAP | Business Gap |
| IA | Artificial Intelligence |
| VR | Virtual Reality |
| AR | Augmented Reality |
| RFID | Radio Frequency Identification |
| IoT | Internet of Things |
| FLQ-OWA | Fuzzy Linguistic Quantifier Order Weighted Aggregation |
| FLW | Food Losses and Waste |
| WSN | Wireless Sensor Network |
| BLE | Bluetooth Low Energy |
| JMBoF | Framework used for inspecting the quality of dry soybean |
| LRR | Simple Linear Regression Method |
| SVR | Support Vector Regression (Machine Learning Algorithm) |
| AdaBoost | Adaptive Boosting (Machine Learning Algorithm) |
| PCA | Principal Component Analysis |
| ABAC | Attribute-Based Access Control |
| BIM | Building Information Modeling |
| AUT | Automation |
| CPS | Cyber-Physical Systems |
| BDA | Big Data Analysis |

| | |
|---|---|
| CC | Cloud Computing |
| AM | Additive Manufacturing |
| VRAR | Virtual Reality and Augmented Reality |
| SIM | Simulation |
| GSU | Grain Storage Unit |
| M2M | Machine-to-Machine |
| TI | Information Technology |
| ODS | Sustainable Development Goals |
| ESG | Environmental, Social and Governance |
| GR | Waste Management |
| NR | Regulatory Standards |
| GEE | Greenhouse Gas Emissions |
| EBITDA | Earnings Before Interest, Taxes, Depreciation, and Amortization |
| P&D | Research and Development |
| LGPD | General Data Protection Law (Brazil) |
| GDPR | General Data Protection Regulation (EU) |

SUMMARY

# 1 INTRODUCTION

The post-harvest stage of grains is a critical component of the global food supply chain, bridging the gap between the intensive agricultural cultivation and the needs of a growing and increasingly globalized population. Brazil, a leading global grain producer, plays a significant role in this process. During the 2022/23 harvest, Brazil produced 312.4 million tons of grains, underscoring its major position in global agricultural production. Despite this achievement, Brazil faces considerable challenges, particularly related to grain storage. The country's static grain storage capacity is 183 million tons, distributed across more than 17,000 storage units, as reported by the National Supply Company (CONAB, 2023).

United Nations projections for 2024 estimate that the world population will reach 8.5 billion by 2030 and 9.7 billion by 2050 (Figure 1).

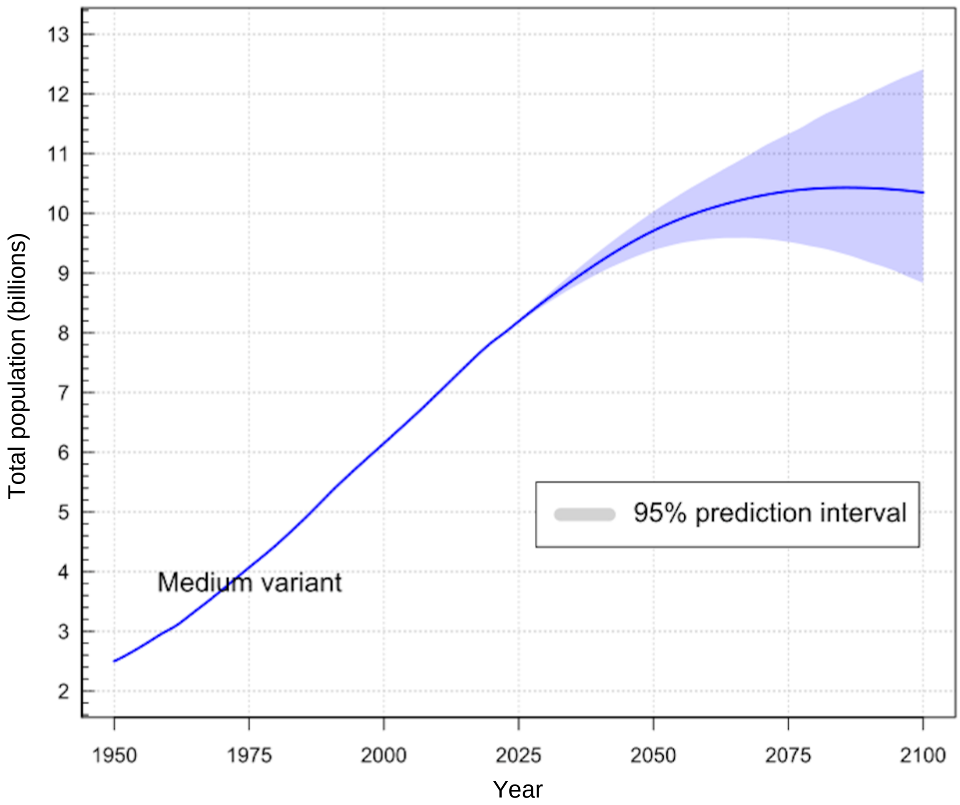


Figure 1. World Population 1950 - 2100. Source: United Nations (2024).

The projected peak global population is approximately 10.4 billion by the 2080s, with this number expected to remain stable until 2100 (United Nations, 2024).

Addressing the challenges of this growing population and preparing our agri-food systems for the future is crucial. The Food and Agriculture Organization of the United Nations (FAO), in its strategic framework for 2022-2031 (FAO, 2021), envisions a sustainable world where food safety is universally achieved. This vision emphasizes enhanced production, improved nutrition, better environmental stewardship, and improved quality of life. The FAO highlights the need for a significant increase in food production to meet the demands of a growing global population. Factors influencing this increase include changes in agricultural practices, efficient use of natural resources, reduction of food loss and waste, technological advancements in agriculture, and improvements in food distribution and access (FAO, 2021).

As the global population increases, the availability of arable land per capita decreases. For instance, while there were approximately 0.52 hectares of arable land per capita in 1950, this figure is projected to decrease to 0.17 hectares by 2050 (Chandra et al., 2021). Additionally, climate change exacerbates water scarcity, further stressing the need for increased productivity in agricultural systems (Hrustek et al., 2020).

Agriculture, particularly grain and cereal production, is vital for feeding both human and animal populations. For example, producing 1 kg of beef, pork, or poultry requires 7, 4, and 2 kg of grains, respectively (Godfray et al., 2010). Companies that provide post-harvest solutions must continue to innovate and adapt to ensure food safety and prevent global shortages. Digital technologies can enhance productivity in this sector (Di Vaio et al., 2020). Studies by Qin et al. (2012) in both developed and developing countries demonstrate the success of digital transformation in managing agri-food systems.

Digital transformation encourages companies to experiment with and develop new business approaches (Westerman et al., 2015). Thompson et al. (2020) note that its effects are profound, with the potential to reshape entire sectors, integrate products and services, introduce new ventures, and present innovative value propositions. It involves various digital innovations and technologies that introduce new actors, structures, practices, values, and beliefs, thereby altering or complementing existing ecosystems across different industries (Westerman et al., 2014).

In traditional sectors, digital transformation is crucial for maintaining competitive advantages (Berman, 2012; Fitzgerald et al., 2014; Gray et al., 2013). It differs from other evolutionary strategies due to its rapid pace of change (Sebastian et al., 2017; Svahn et al., 2017). This digital revolution introduces greater volatility, complexity, and uncertainty, necessitating adjustments in business models, organizational structures, and processes (Dattée et al., 2018; Loonam et al., 2018; Matt et al., 2017).

Digitalization creates opportunities for enhanced customer interaction, often resulting in innovative business models (Aspara et al., 2013; Chesbrough et al., 2010; Khanagha et al., 2014; Wirtz et al., 2010). Organizations with skills that drive transformation typically foster agile and entrepreneurial mindsets, emphasizing external networks (Day et al., 2016). These skills support strategic renewal processes, adapting resources and structures to ensure flexibility in changing digital environments (Agarwal et al., 2009; Teece et al., 2014).

Transforming digital business models requires aligning corporate models and business units through interdependent decision-making (Aspara et al., 2013; Velu et al., 2013). Companies often rely on past experiences to manage strategic complexity, balancing agility and stability, certainty and uncertainty, or short-term and long-term benefits (Laudien et al., 2016; Doz et al., 2010; Gavetti et al., 2000; Demil et al., 2010).

This study aims to advance the understanding and implementation of digital solutions in post-harvest management, addressing current challenges and future perspectives, and contributing to a more resilient and efficient agricultural sector.

## 1.1 RESEARCH THEME

Post-harvest activities encompass companies in the metal-mechanical sector that deliver engineering solutions for the grain industry. These companies are responsible for maintaining grain quality from harvest through to its use by agribusinesses, retailers, and end consumers (Hossen et al., 2020). For suppliers of post-harvest equipment, digital transformation presents an opportunity to evolve their business models. Traditionally, these companies have focused primarily on selling physical products such as storage silos, handling equipment, cleaning machines, and dryers. Currently, with the advent of digital technologies, these companies can integrate services into their product offerings (Dyck et al., 2022). However, there remains a need to understand how digital transformation affects their business models. Identifying the necessary capabilities and key opportunities that digital transformation can provide is essential for generating new revenue streams (Kayikci et al., 2022).

## 1.2 RESEARCH QUESTION AND OBJECTIVES

This research addresses the issue that manufacturers of post-harvest solutions have not fully understood the implications of digital transformation on their operations. The research question is: How can companies providing post-harvest solutions capitalize on the digital transformation occurring in the sector?

The study's objectives are categorized into a general objective and specific objectives.

### 1.2.1 GENERAL OBJECTIVE

Analyze the challenges and opportunities of digital transformation identified for post-harvest solutions companies.

### 1.2.2 SPECIFIC OBJECTIVES

The study comprises three specific objectives that collectively address the general research objective. These objectives are as follows:

a) Provide descriptive and quantitative statistics to establish a connection between digital technologies and critical control points within a grain post-harvest system.

b) Analyze the opportunities and challenges that digital transformation in post-harvest activities presents to an engineering solutions provider.

c) Analyze the impacts of digital transformation on the performance of a company in the post-harvest sector, identifying strategies to overcome the challenges associated with this transition.

## 1.3 JUSTIFICATION

The exponential increase in scientific publications related to digital transformation and enabling technologies for grain post-harvest since 2001 (Figure 2) highlights the growing significance of this research area. The digital revolution and associated technologies are becoming increasingly essential for enhancing and optimizing grain post-harvest processes. This importance is underscored by the rising global food demand, which necessitates an understanding of how these innovations can contribute to more effective and sustainable food production. This research area spans multiple disciplines, including agriculture, engineering, information technology, logistics, and management. Consequently, it offers a valuable opportunity to integrate and apply interdisciplinary knowledge to address complex challenges.

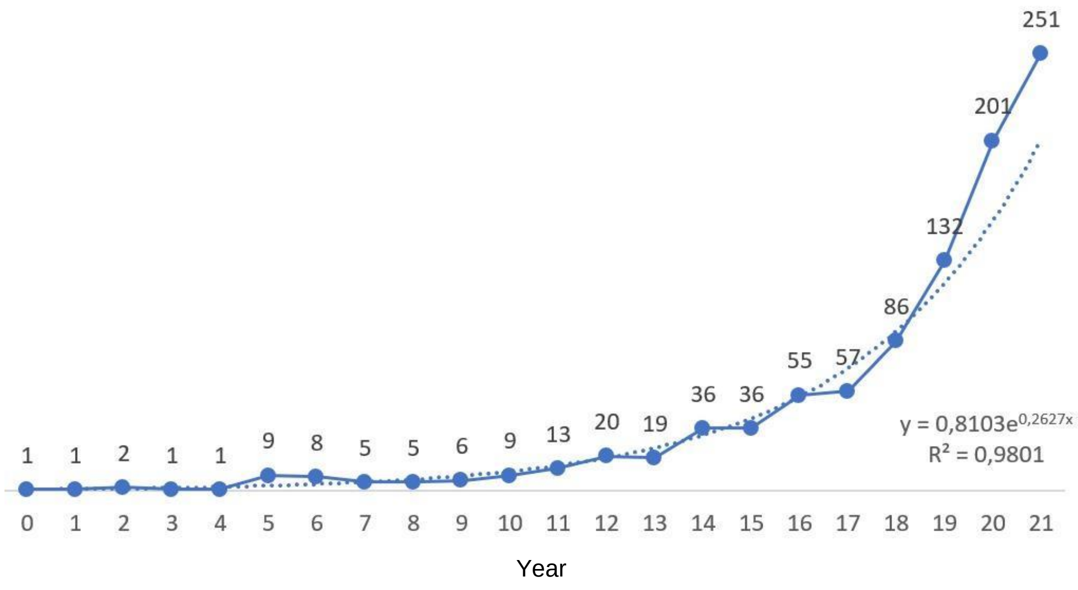


Figure 2. Scientific Publications between 2001 and 2022. Source: Scopus (2023)

Despite the extensive research, a comprehensive understanding of the implications of digital transformation for grain post-harvest processes remains lacking. This study addresses this gap by consolidating dispersed information and providing a cohesive global perspective. As technology continuously evolves, this research aims to contribute to the academic knowledge base by analyzing current trends and exploring their effective application.

The increase in grain production, driven by advancements in precision agriculture, has enhanced the application of inputs, machinery, and natural resources, leading to higher yields (Khanal et al., 2017). Investments in farming are expected to translate into improved post-harvest yields (Cafiero et al., 2018). However, technologies that ensure high-quality grain storage are also necessary to maximize profitability for farmers and the industry (Coradi et al., 2014; Duysak et al., 2021).

Post-harvest processes encompass various stages at the end of the grain production chain, influencing sector logistics through transportation and storage (Ali et al., 2020; Hirano et al., 2022; Toosi et al., 2022). Losses during these stages can result from metabolic changes in grain, environmental conditions, processing actions, and product movement (Toosi et al., 2022).

Exploring the opportunities provided by digital transformation in post-harvest activities can lead to more sustainable agricultural practices and enhance global food safety. Improving efficiency in grain storage and handling is crucial for reducing food waste throughout the supply chain. For instance, ensuring soybeans are stored at 13% moisture content is essential for safe storage (MAPA, 2010). Digital technologies in drying processes can minimize operational errors, which are economically significant. For example, a 1% error in drying could result in substantial losses, with a silo containing 100,000 sacks of soybeans potentially incurring losses of USD 28,000 per silo. With Brazil projected to produce 153.8 million tons of soybeans in 2023, a 1% error could lead to losses of USD 0.7 billion. Digital technologies can help reduce such losses by improving monitoring and control of drying humidity.

Another aspect of food safety involves the prevention of microorganisms that cause grain deterioration. For instance, Aspergillus flavus, which thrives in conditions of 30°C and 70% relative humidity, has high carcinogenic properties and poses a risk to grain quality (Christensen et al., 1974). Digital technologies can help manage storage conditions to prevent such contamination.

Implementing digital technologies in post-harvest activities can have significant financial implications for both solution providers and clients. Reducing operational errors and optimizing resource management can minimize economic losses and enhance profitability. Furthermore, maintaining high-quality products and preventing losses can improve supply chain reliability and foster stronger commercial relationships.

The socio-environmental benefits are also notable, as reducing food waste lessens greenhouse gas emissions and conserves natural resources (Bartali et al., 2022). Digital transformation enables more efficient resource use, contributing to environmental sustainability goals. The research aims to identify digital practices that preserve essential resources, positively impacting the environment and rural communities.

Additionally, digital transformation creates job opportunities in technology and engineering, promoting economic and social development in rural areas. It enhances the resilience of the food supply chain, which is vital for addressing climate change and global crises, such as the COVID-19 pandemic. This research supports various UN Sustainable Development Goals, including SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

Overall, this study on digital transformation in grain post-harvest activities in Brazil not only explores commercial challenges and opportunities but also addresses significant socio-environmental issues, advancing sustainable agricultural practices, reducing food waste, and contributing to global sustainability goals.

## 1.4 RESEARCH DELIMITATIONS

This research focuses on the agriculture sector, specifically the grain post-harvest segment. It examines companies within the metal-mechanical industry that provide critical solutions for this sector. These companies are essential for delivering technologies and solutions that maintain the quality and integrity of grains or cereals from harvest through their final use by the industry and consumers.

The study emphasizes the role of metal-mechanical industries in ensuring grain quality and preservation during the post-harvest phase, which is crucial for food safety and supply chain efficiency. This focus underscores the study's significance for both the academic community and the industrial sector.

However, this research does not cover other phases of the agricultural cycle, such as planting, harvesting, or final distribution of agricultural products. It also excludes technologies and industries outside the scope of metal-mechanical solutions for post-harvest grain processes. Thus, the study is specifically delineated to address digital innovations in the metal-mechanical industry relevant to post-harvest grain management, without extending to unrelated areas.

# 2 METHODOLOGY

This chapter outlines the methodological procedures employed to achieve the objectives of this dissertation.

Research can be classified into four main categories based on its nature, approach, objectives, and methods or procedures (Nielsen et al., 2018). To understand the process, it is essential to describe the data sources and research instruments used. Figure 3 provides a concise overview of the characteristics of this research.

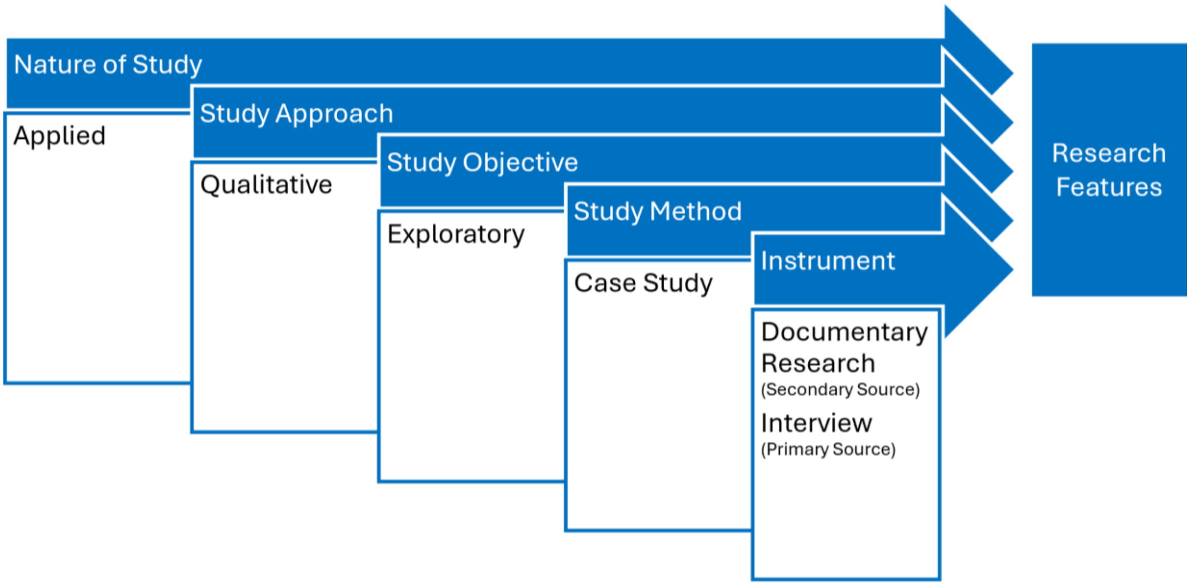


Figure 3. Research Characteristics. Source: Author

Silva and Menezes (2005) classify research based on its nature into two categories: basic and applied. The distinction between these classifications lies in the practical application of the research. This study falls under applied research, as it aims to generate knowledge for practical use and addresses specific problems (Silva & Menezes, 2005; Gil, 2010).

The approach of this study is qualitative, focusing on understanding and exploring the impacts of digital transformation within the selected case. Qualitative research seeks to comprehend the processes and meanings behind phenomena, immersing in the subject to gather detailed descriptions of facts, situations, and interactions, thereby achieving a deeper understanding (Cooper & Schindler, 2011; Sampiere et al., 2013).

Gil (2010) defines exploratory research as aiming to enhance familiarity with a research problem, clarify it, or develop hypotheses. Nielsen et al. (2018) add that exploratory research focuses on gaining a better understanding or detailing aspects of a relatively unknown phenomenon. This research is exploratory in nature because the process of digital transformation in post-harvest solution providers is still not well understood.

To address the objectives outlined, this study employs a case study method. Figure 4 outlines the methodology employed in the development of this case study, describing the workflow from the definition and planning stages through to preparation, data collection, analysis, and finally, the concluding phase.

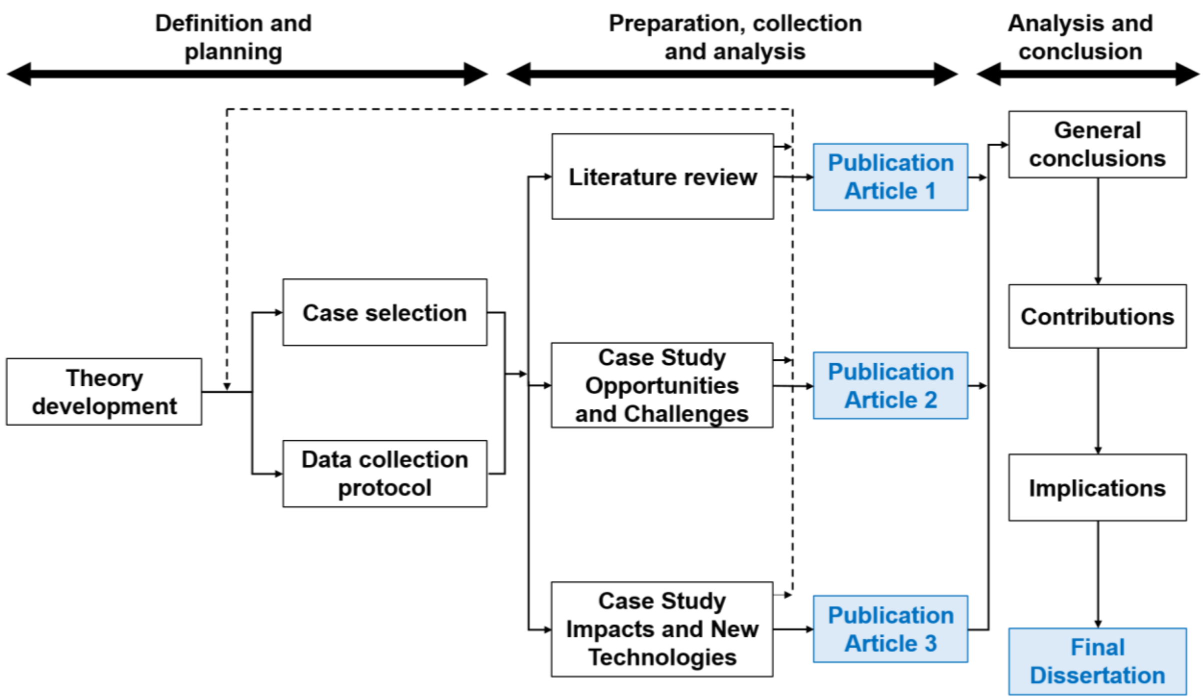


Figure 4. Applied methodology in the case study. Source: Author

The research objectives and method were initially defined, establishing a foundation for the subsequent phases. Alongside the planning process, the first academic article was developed, focusing on a bibliometric review that provided a solid framework for understanding trends and identifying gaps in the literature.

In the subsequent phase of preparation, data collection, and analysis, two case studies were conducted. The first addressed the opportunities and challenges within the field, leading to the publication of the second article. The second case study incorporated empirical research, analyzing impacts and international connections, which resulted in the third article.

The final stage, analysis and conclusion, synthesized the findings and compiled the outcomes into the final dissertation.

This methodological process followed a structured and logical sequence, ensuring that each phase contributed significantly to the results and the formulation of the final conclusions. The subsequent sections will provide detailed information on the specifics of this method, including the selection process and implementation procedures.

## 2.1 CASE STUDY

The case study method is frequently employed in social sciences and business administration research (Nielsen et al., 2018; Gil, 2010; Martins, 2006). This method is particularly useful for addressing research questions that seek to understand "how" and/or "why" specific phenomena occur, providing insights into phenomena within one or more organizations (Nielsen et al., 2018; Yin, 2015; Cooper & Schindler, 2011).

According to Nielsen et al. (2018), the objective of a case study is to gain an in-depth understanding of a specific phenomenon or reality, emphasizing detailed exploration and source triangulation while potentially limiting broader scope. Pereira (2010) characterizes a case study as an exhaustive investigation of one or a few objectives, aimed at achieving comprehensive and detailed knowledge.

Yin (2015) describes the case study approach with a dual perspective:

(i) Regarding scope, the case study is an empirical investigation that:

a. Investigates a contemporary phenomenon (the "case") in depth and within its real-world context, especially when

b. the boundaries between the phenomenon and the context cannot be clear and evident.

(ii) Regarding the investigative characteristics of the case study, it presents the following features:

a. Faces the technically differentiated situation where there will be far more variables of interest than data points, and as a result.

b. Relies on multiple sources of evidence, with data needing to converge in a triangulated manner, and as another result.

c. Benefits from prior development of theoretical propositions to guide data collection and analysis.

The case study method is selected for this research to explore "how" digital transformation affects the chosen company and sector. As noted in the introduction, digital transformation is a continuous process that is difficult to isolate from the business context, given that companies have already reached a critical point in this process (Hess et al., 2016).

For this study, it is essential that the selected case, or unit of analysis, is both original and insightful (Martins, 2006), as well as relevant (Yin, 2015). The subsequent section will detail the rationale for selecting Kepler Weber S.A. as the unit of analysis for this research.

## 2.2 CASE SELECTION

The case study method can encompass a single case or multiple cases. Yin (2015) identifies five main justifications for using a single case study: critical, unique, common, revelatory, and longitudinal. Moreover, the case must be connected to relevant theoretical propositions, which increases its significance.

For this research, the post-harvest grain sector was selected due to its substantial potential for integrating new digital technologies, which are essential for driving digital transformation. This sector plays a crucial role in agriculture, directly impacting the national Gross Domestic Product (GDP), and its technological solutions may be applicable to other service sectors.

Kepler Weber S.A. (KEPL3), a publicly traded company with a century of history, develops solutions for grain storage and bulk handling. As a leading supplier of post-harvest grain management equipment in Latin America, the company operates in more than 53 countries and is the largest producer of grain silos in Brazil. Listed on the stock exchange since 1980, Kepler Weber reached a net revenue of R$ 1.5 billion (USD 300 million) in 2023, holding 40% of the post-harvest market share in Brazil. With two manufacturing plants and nine distribution centers across the country, the company can simultaneously manage up to 300 grain storage projects, with an average capacity of 5.6 million tons of grain annually.

Given that this study focuses on the digital transformation of post-harvest operations, Kepler Weber S.A. emerges as a pertinent subject of analysis. Its market-leading position and the fact that it is the first Brazilian company to explicitly incorporate digital activities into its strategic objectives, as documented in public reports, make it a unique opportunity for a longitudinal study on digital transformation.

The impact of Industry 4.0, launched by the German government in 2012, was significant for the company. The empirical research on best international practices involved collaboration with the Bremer Institut für Produktion und Logistik GmbH (BIBA), a research institution affiliated with the University of Bremen. Founded in 1981, BIBA is renowned for its applied research in production and logistics, aligning with Kepler Weber's innovation goals. The partnership with BIBA facilitates the adoption of technologies such as automation and IoT, which are essential for advancing digitization in the post-harvest sector.

In this study, the non-participant direct observation technique will be employed, allowing the researcher to closely monitor the company's key activities in real-time without influencing the outcomes. This approach will provide valuable insights into the implementation of digital technologies and their practical implications for transforming operations.

## 2.3 DATA SOURCE OF THE RESEARCH

Cooper and Schindler (2011) describe the case study as a versatile research methodology that can integrate various data collection methods, including individual or group interviews, record analysis, and observation. Yin (2015) outlines six techniques commonly employed in case studies:

- documents - letters, memoranda, agendas, announcements, administrative documents, reports, etc.
- records in archives - publicly accessible archives, such as censuses or other government data, service records, organizational records, maps, and charts of geographic features.
- guided interviews, which may follow structured or semi-structured protocols. They can be open-ended, group, or individual.
- direct observations - on-site, through visual confirmation of a fact during field visits, and of specific behavior over periods of time.
- participant observations - in this mode, the interviewer is not passive but participates in the events studied, for example, in studies of social interactions. Widely used in anthropological studies.
- physical artifacts - evidence of a physical or cultural artifact such as a technological device, tool, or instrument, artwork, or some other physical evidence.

In this study, both documentation and interviews are utilized. Yin (2015) emphasizes the importance of using multiple sources of evidence to corroborate information and achieve the necessary triangulation for case studies.

Documentary sources will include materials provided by the company and relevant scientific articles. Yin (2015) asserts that documents are valuable for corroborating and augmenting evidence from other sources, which aids in validating the collected data.

Interviews serve as a primary source of information for the case study (Yin, 2015; Cooper & Schindler, 2011). Typically, these interviews take the form of guided conversations, also referred to as intensive, in-depth, or unstructured interviews.

## 2.4 DATA ANALYSIS AND PRESENTATION

According to Cooper and Schindler (2011), case study analysis focuses on understanding variations in phenomena, exploring the reasons and mechanisms behind their occurrence, and drawing prescriptive inferences about best practices based on the study's findings. Martins (2006) further elucidates that this stage aims to capture the essence and substance of the context from the available data and information, thereby uncovering the causes, antecedents, effects, and consequences of the phenomenon.

Yin (2015, p. 136) describes data analysis as involving the examination, categorization, tabulation, hypothesis testing, or recombination of evidence to produce empirically grounded findings. The data collected as outlined in this methodology chapter will inform the subsequent stages of the research.

The initial stage involves addressing the identified problem through a bibliometric and systematic literature review. This comprehensive review seeks to build a robust foundation of scientific knowledge on the topic. By analyzing existing literature, the objective is to identify key trends, methodologies, and findings related to digital technologies in grain post-harvest processes, both in Brazil and globally.

The bibliometric review will quantify and analyze trends in academic research, identifying influential authors, key journals, and relevant conferences. The systematic review will map and synthesize pertinent studies, categorize findings, and highlight gaps in current knowledge.

The Scopus database will be utilized for researching digital transformation in post-harvest grains due to its extensive range of titles. Other databases, such as EBSCOhost and CAPES, have been found to offer limited contributions. Search keywords will be based on various digital technologies relevant to the grain post-harvest sector. Keywords include: "post-harvest" OR post-harvest OR "grain storage" AND grains AND (automation OR "radio frequency identification" OR RFID OR "cyber-physical systems" OR "internet of things" OR IoT OR "virtual reality" OR "augmented reality" OR "big data" OR "cloud computing" OR simulation OR "artificial intelligence" OR "additive manufacturing" OR blockchain OR "digital twin"). Table 01 presents the filters and keywords used in the initial research stage.

| Attribute | Filter |
|---|---|
| Research database | Scopus |
| Year | Up to 2022 |
| Author's name | No filter |
| Research area | No filter |
| Document type | Limited to articles |
| Country | No filter |
| Research line | Any field |
| Language | No filter |

Table 1. Attributes and filters for the bibliographic search. Source: Author

The research, conducted in June 2023, includes references up to 2022, resulting in a total of 3,504 scientific articles. The screening process consisted of three stages: identification, eligibility, and definition. Exclusion criteria included keywords such as apple, trees, pineapple, carrot, tobacco, grape, passion fruit, avocado, jackfruit, strawberry, lettuce, tomato, banana, kale, spinach, cauliflower, eggs, blueberry, cowpea, breadfruit, wasps, vegetation, kiwi, grapefruit, peach, and "heavy metal". Figure 5 illustrates this process.

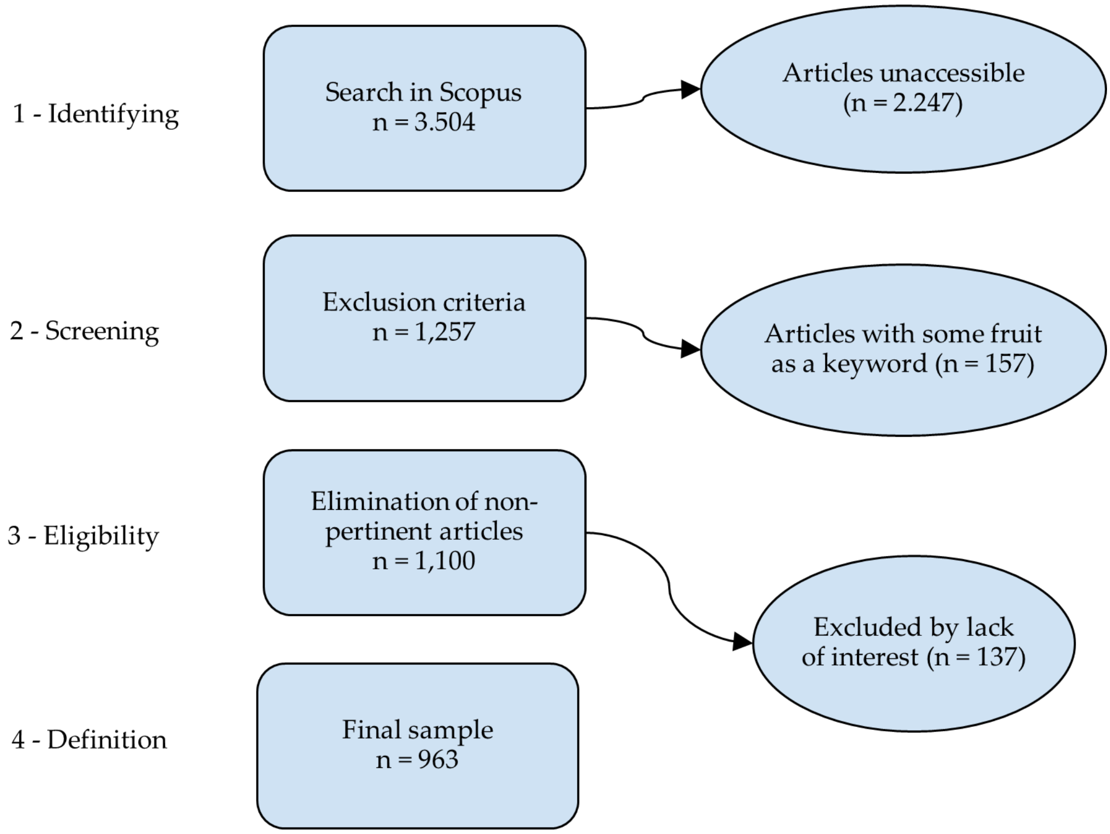


Figure 5. Flowchart of the bibliographic search. Source: Author

Initial exclusion criteria removed articles with restricted access, reducing the number to 2,247. Further exclusion was based on the presence of fruit-related keywords in titles, abstracts, or keywords, eliminating 157 articles. The eligibility stage did not identify duplicate files. A subsequent review, using specific keywords, excluded 137 articles deemed irrelevant to the research topic. The final sample comprised 963 articles relevant to bibliometric and descriptive analysis.

This stage provides a comprehensive overview of the scientific literature and aims to precisely characterize the problem by identifying key dimensions, causes, consequences, and impacts on the food supply chain. The literature review will highlight the problem's relevance in economic, social, and environmental contexts. This foundational analysis will support a deeper understanding of digital technologies for grain post-harvest and lay the groundwork for subsequent research stages.

In the second stage, the research employs a single case study to identify empirical solutions applied by the studied company. This method allows for the analysis of practical examples related to grain storage, transportation, and handling in Brazil. The case study focuses on a Brazilian company specializing in engineering solutions for post-harvest activities, using non-participant direct observation to monitor key activities in real time.

The study involves the following stages:

(i) Collection and analysis of documents from the engineering solutions provider.

(ii) Guided tours of the company's facilities and two customer sites, with company professionals.

(iii) Interviews with the company's portfolio managers and specialists.

(iv) A final meeting where findings are presented to managers for validation and potential adjustments.

This study does not quantify losses but explores opportunities for future innovation. The findings are specific to the research context, and broader external validity would require sector-wide studies. The final meeting with participants enhances the study's internal validity and reliability. As an exploratory and qualitative study, it provides a descriptive analysis of phenomena and stimulates further research without using mathematical models.

In the third stage, the research will benefit from collaboration with the Bremer Institut für Produktion und Logistik (BIBA) in Bremen, Germany. This stage combines a case study of a Brazilian company with an analysis of international best practices at BIBA. BIBA's focus includes application-oriented research in production and logistics across various sectors. Employing non-participant direct observation to monitor key activities in real time, the study includes:

(i) Collection and analysis of documents and technologies from BIBA.

(ii) Guided tours of BIBA's facilities with involved professors and professionals.

The empirical research at BIBA involves qualitative and quantitative analyses of impacts and technological trends relevant to digital transformation. The findings are expected to be valid within the research scope, with broader validity requiring additional sector-wide studies. The final meeting with participants at BIBA enhances the study's internal validity and reliability. The exploratory nature of this research provides a descriptive analysis and encourages further investigation.

The fourth stage involves disseminating research results through publications in academic journals, conferences, and other forums. This stage aims to share knowledge with the scientific and professional communities, promote discussion, and influence practice and decision-making in grain post-harvest management. It includes presentations at conferences, workshops, and seminars, as well as creating outreach materials for industry professionals and policymakers.

Table 2 highlights the diversity and qualifications of the interviewees, all of whom have relevant experience in grain post-harvest processes and/or in research that develops new technologies.

| Research Object | Activity | Academic Background | Degree |
|---|---|---|---|
| Company | Director of Digital Services | Administration | Master's |
| | R&D Coordinator | Chemical Engineering | Bachelor's |
| | Product Engineer | Agricultural Engineering | Bachelor's |
| | Product Owner | Agricultural Engineering | Doctorate |
| | Automation Analyst | Electrical Engineering | Bachelor's |
| | Electrical Designer | Electrical Engineering | Bachelor's |
| | Technology Product Analyst | Computer Science | Bachelor's |

| | | | |
|---|---|---|---|
| | Storage Unit Manager (Customer) | Agricultural Engineering | Bachelor's |
| | Storage Unit Manager (Customer) | Agricultural Engineering | Master's |
| Research Institute | Scientific Director | Electrical Engineering | Doctorate |
| | Research Coordinator | Engineering Economics | Bachelor's |
| | Researcher | Aerospace Engineering | Master's |
| | Researcher | Industrial Engineering | Bachelor's |
| | Researcher | Mechanical Engineering | Bachelor's |

Table 2. Profile of Interviewees.

The methodology of unstructured interviews used for data collection allowed for a more flexible and interactive approach, enabling the exploration of specific perceptions and experiences of the participants. This contributed to the collection of deep insights into the implementation of emerging technologies in the agricultural sector.

## 2.5 DISSERTATION STRUCTURE

The thesis is organized into six chapters, each addressing distinct aspects of the research. The first chapter introduces the study, presents the rationale, and outlines the research objectives. The second chapter details the methodological procedures employed. The results derived from these procedures are presented in chapters three, four, and five, each of which constitutes an independent article (see Figure 6).

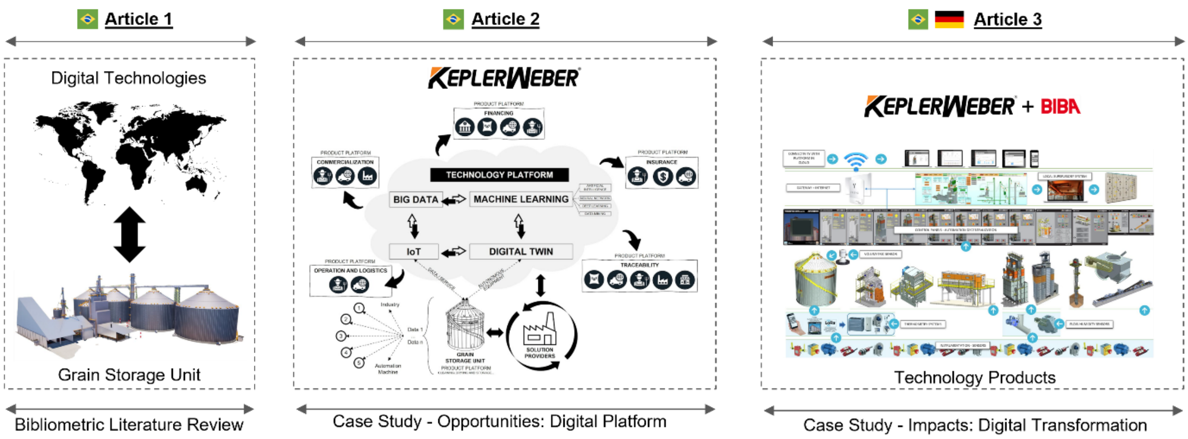


Figure 6. Articles for the Dissertation. Source: Author

Chapter Three presents the first article, published in Sustainability (2024, 16(3), 1244; https://doi.org/10.3390/su16031244). This chapter features a comprehensive bibliometric review of the literature, including descriptive statistics that establish the connection between digital technologies and critical control points within a grain post-harvest system. To ensure transparency and replicability, a detailed protocol outlining the adopted methodology is provided. The chapter also includes a thorough evaluation of both quantitative and qualitative aspects of the historical data analyzed.

Chapter Four corresponds to the second article, published in AgriEngineering (2023, 5(3), 1226-1242; https://doi.org/10.3390/agriengineering5030078). This chapter explores the opportunities and challenges of digital transformation in adding value to customers in post-harvest operations. Using a case study approach, the research focuses on a company in southern Brazil that provides integrated digital engineering solutions for grain producers. The chapter aims to describe the company's digital products and services, analyze the key opportunities for value creation, identify relevant stakeholders, and assess how these stakeholders benefit from digitalization.

Chapter Five presents the third article, which provides an in-depth analysis of the company's journey towards digital transformation, highlighting the associated challenges. This chapter focuses on assessing the impacts of digital transformation on the company’s outcomes, aiming to understand how new technologies can address these challenges. This article was developed in collaboration with researchers from BIBA (Bremer Institut für Produktion und Logistik GmbH) in Bremen, Germany, enriching the research through international exchange and global knowledge sharing.

Chapter Six concludes the dissertation by discussing the findings, outlining the limitations encountered, and offering recommendations for future research. Through the integration of these three articles, the dissertation provides a comprehensive examination of the role and impact of digital technologies in the post-harvest grain sector, contributing to the advancement of academic knowledge.

# 3 FIRST ARTICLE - DIGITAL TECHNOLOGIES, SUSTAINABILITY, AND EFFICIENCY IN POST-HARVEST ACTIVITIES: BIBLIOMETRIC ANALYSIS

## ABSTRACT

Post-harvest grain processes play a crucial role in food supply chains, encompassing various agricultural and environmental aspects. Recent research focuses on how digital technologies can minimize grain losses, enhance food safety, and reduce environmental impacts but lacks clarity on the relationship between technologies and the objectives of efficiency and sustainability, particularly concerning critical control points in post-harvest activities. The purpose of this article is to establish a connection between digital technologies used in food supply chains and critical control points within post-harvest systems. The research method is a bibliometric analysis. A survey of recent literature identified thirteen digital technologies. Previous research identified nine critical control points in post-harvest engineering solutions, responsible for most losses in efficiency and environmental impacts. Using a sample of case studies from recent literature, a framework was constructed to relate digital technologies and critical control points. The primary contribution of the study lies in a categorized list of the most influential technologies corresponding to each control point. The significance and novelty lie in providing managers and practitioners in engineering solutions for post-harvest systems with a practical guide for decision-making in the se-lection of technologies for future projects. Ultimately, this aids in reducing losses and environ-mental impact.

**Keywords:** digital transformation; digital technologies; post-harvest; grain storage; agribusiness.

## 1 INTRODUCTION

In contemporary agribusiness, there is a consistent demand for new digital technologies in the food supply chain (FSC). Digitalization can play a relevant role in creating value for rural activities, acting in more than one dimension, like activities, flows, or governance methods [1]. Particularly in grain post-harvest systems, digitalization aims to address factors affecting food production and quality, safety, and environmental impacts, which are crucial for efficiency [2]. A significant challenge in the FSC is grain storage [3], which historically has been perceived as a unique ecosystem due to its magnitude and significance for human survival [4], akin to the concept of the technosphere or agro-industrial landscapes [5].

Research concerning grain storage encompasses various aspects. The management is intricate due to the multiple stages involved [6] and diverse forms of distribution [7]. Studies have been conducted to mitigate grain losses both pre- [8]

and post-harvest [9]. The literature discusses, compares, and evaluates grain storage techniques, encompassing the utilization of solar energy [10], non-chemical alternatives for pest control [11], and intelligent technological interfaces that enhance management and control [12]. Additionally, real-time online monitoring systems are explored to alleviate uncertainty in market availability, food safety, and food quality [12]. Research on post-harvest digital transformation aligns with the broader context of reducing food waste and promoting sustainability [13,14,15]. Concerning the grain quality, the primary focuses include moisture control, insect infestation, and toxin contamination [16,17,18].

Grain commodities play a pivotal role in the economies of numerous countries. Presently, Brazil and the USA stand as the primary exporters of corn and soybeans. Together with China, these nations account for most of the global corn production. Notably, Brazil currently faces a static storage capacity deficit of approximately 70 million tons, based on the FAO (Food and Agriculture Organization) of the United Nations' recommendation that a country's static storage capacity should be 1.2 times its annual production [19].

From both local and global perspectives, there is an essential need to comprehend how digital transformation technologies affect grain storage, which could significantly influence the agricultural potential for grain exports in many countries [20]. In numerous developing countries, silo facilities often fall short of meeting adequate requirements due to issues like poor hygiene, insufficient grain drying, inadequate transportation, and other related logistical challenges [21].

Considering the role of grain storage in the global food supply chain, numerous studies have contributed to knowledge in this domain and proposed various application possibilities. Although some reviews, such as [22], have scrutinized literature related to grain storage, these reviews need to delve into digital technologies applied to FSC and mainly to post-harvest activities. As post-harvest engineered systems are complex, intricate installations, the identification of critical control points (CCP) is required [23]. Therefore, the research gaps this study aims to bridge is to find what digital technologies apply to improve the effectiveness of post-harvest engineered systems. The purpose of this study is to establish a connection between digital technologies employed in FSC and critical control points within post-harvest management systems. The method is a bibliometric analysis. The intermediate objectives are to lead a review of the proper literature to identify what digital technologies apply to FSC and to find application cases to correlate each technology with each CCP in post-harvest engineered systems. The rest of the article is structured by the methodology, results, and final remarks.

## 2 MATERIALS AND METHODS

Bibliometrics allow the global state of science and technology to be observed by analyzing scientific production stored in a data repository. It relies on counting scientific articles, patents, and citations. Depending on the study’s purpose, data can consist of publication text or elements extracted from bibliographic databases, including author names, titles, sources, language, keywords, classification, and citations [24]. Bibliometrics help in identifying trends in knowledge growth, dispersion, and obsolescence in a discipline, as well as the most productive authors, institutions, and journals used for research dissemination in a specific knowledge area.

This study utilized data from Scopus articles on digital transformation in post-grain harvest due to the extensive title availability. Other databases like EBSCOhost and CAPES lacked significant contributions. Research keywords were established based on diverse digital technologies relevant to the post-harvest grain segment. The keywords were the following: (“post-harvest” OR post-harvest OR “grain storage”) AND grain AND (automation OR “radio frequency identification” OR rfid OR “cyber-physical systems” OR “internet of things” OR IoT OR “virtual reality” OR “augmented reality” OR “big data” OR “cloud computing” OR simulation OR “artificial intelligence” OR “additive manufacturing” OR blockchain OR “digital twin”). Table 1 displays the applied filters and keywords used in the initial research stage.

| Attribute | Filter |
|---|---|
| Search base | Scopus |
| Year | Until 2022 |
| Author name | No filter |
| Search area | No filter |
| Document type | Limited to articles |
| Country | No filter |

| Research field | Any field |
|---|---|
| Language | No filter |

Table 01 – Attributes and filters for the bibliographic search.

The research occurred in June 2023 and considered the title, abstract, or keywords of articles up to 2022. The identifying stage yielded 3504 scientific articles. In the screening stage, the articles were separated into accessible and restricted, resulting in 1257 pieces. As the study focuses on grain post-harvest, in the eligibility stage, studies involving fruits were removed, resulting in 1100 articles. In the definition stage, and utilizing specific keywords such as agribusiness or agrifood, 137 articles were identified as non-pertinent, resulting in a final sample of 963 articles. The VOSviewer software version 1.6.19 facilitated data processing, enabling the creation of word and author clouds. The eligibility stage detected no duplicate files. The keywords for fruit's exclusion were apple OR trees OR pineapple OR carrot OR tobacco OR grape OR passion OR avocado OR jackfruit OR strawberry OR lettuce OR tomato OR banana OR kale OR plantain OR kiwifruit OR spinach OR cauliflowers OR tomatoes OR eggs OR blueberry OR cauliflower OR cowpea OR breadfruit OR wasps OR vegetation OR kiwifruits OR grapefruit OR peach OR "heavy metal". Figure 1 depicts the process.

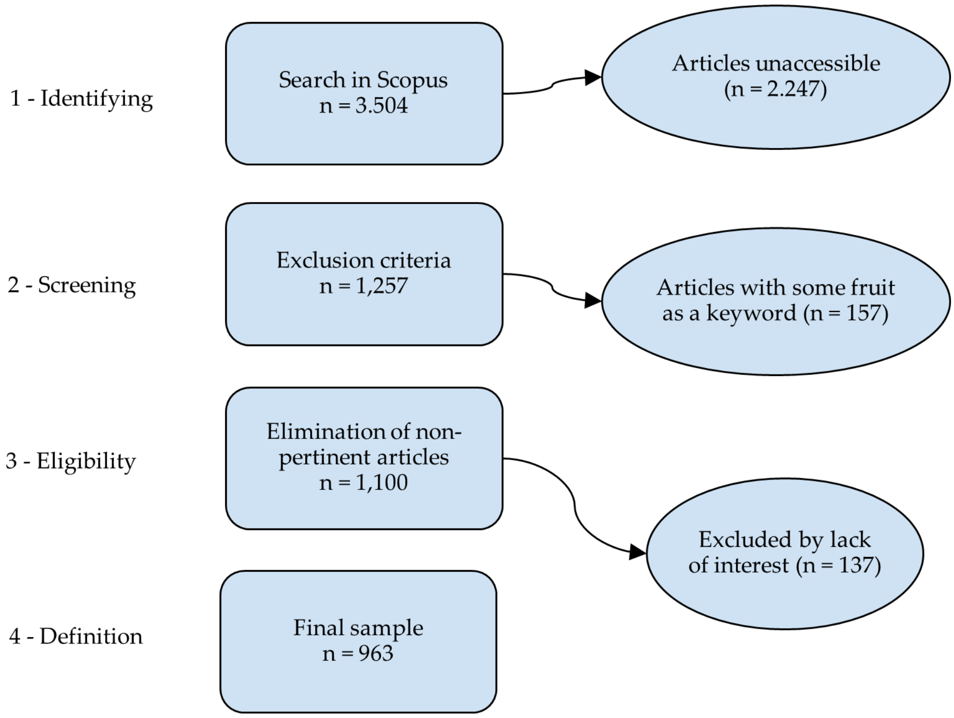


Figure 1 – Flowchart of the bibliographic search.

After the bibliometric analysis, three experts helped to identify how each technology can contribute to improving efficiency and sustainability in grain post-harvest activities.

# 3 RESULTS

## 3.1 Bibliometric Analysis

Despite some isolated early articles, publication was enhanced after 2001. An exponential model applies to the growth in publications. An initial article authored by Reutlinger in 1976 introduced a statistical simulation model assessing the influence of storage capacity levels and associated policies on stabilizing the global wheat supply. From 1976 to 2002, 11 publications focused solely on simulation models. In the subsequent ten years (2003–2012), 59 publications emerged, signaling a modest yet substantial surge in searches (+540%). Among these, 50 centered on simulation models, seven on automation systems, and two on artificial intelligence. This period witnessed the introduction of two technologies, automation and artificial intelligence, previously lacking scientific references but pivotal in the digital transformation of the segment. Notably, the post-2012 era, aligned with the Industry 4.0 movement initiated by the German government, witnessed a noteworthy upswing in scientific publications concerning technologies related to digital transformation for post-harvest grains. From 2013 to 2022, 893 publications encompassing all relevant technologies emerged. Figure 2 depicts the quantitative publication trend from 2001 up to 2022, including only accessible pieces.

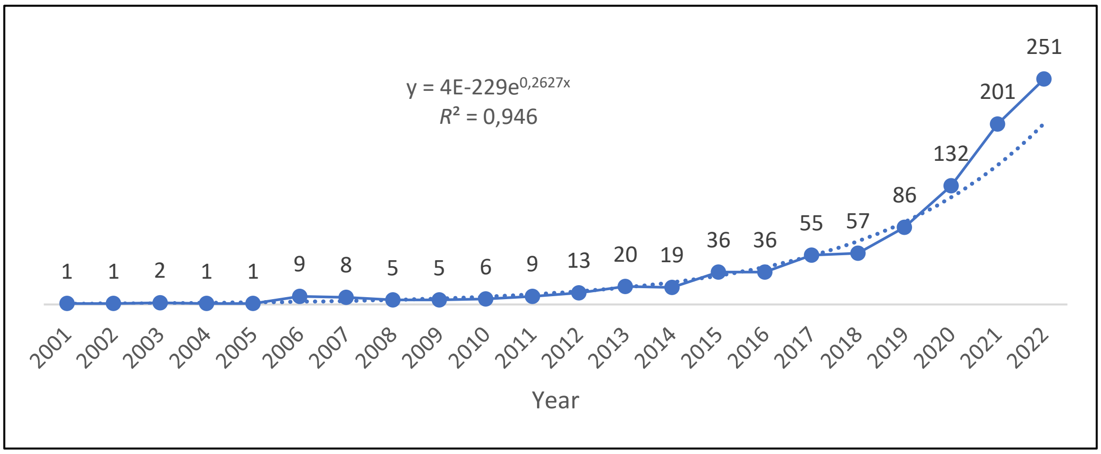


Figure 2 – Number and trend of retrieved publications per year.

The most prolific author is F. Arthur, who holds a Ph.D. in entomology from the University of North Carolina. Since 1986, Arthur has been actively engaged in research and is affiliated with the Manhattan Grain and Animal Health Research Center. His focus lies in applied research addressing insect pest management in stored cereal grains and food warehouses. Among his eleven publications, ten revolve around simulation systems, while one delves into artificial intelligence. Arthur's studies encompass the simulation of more efficient aeration systems, considering climatic data to be decision-making factors. He analyzes the moisture content of stored grains, examining their impact on insecticide use and the occurrence of mycotoxins, directly influencing global food safety. Additionally, his research explores the implications of employing IoT remote management solutions on aeration systems. Lastly, he investigates the efficacy of a hybrid grain dryer employing biomass and solar energy. Figure 3 depicts publications per author.

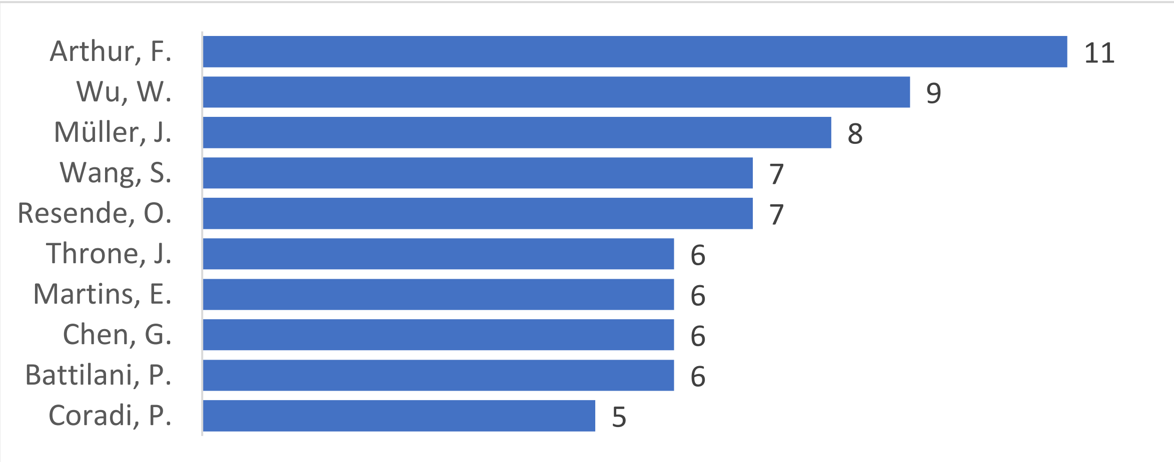


Figure 3 – Number of retrieved publications per author.

China leads in quantity, contributing 23% of publications (223 articles), followed by the United States at 18% (180 articles). Brazil secures the third position, contributing 9% to scientific research (94 articles). Such a position underscores Brazil's significant role in global agricultural production. Among the prominent European contributors, the United Kingdom, Germany, Italy, Poland, Spain, and France collectively produced 280 publications, accounting for 29% of the total articles. Figure 4 depicts publications per country.

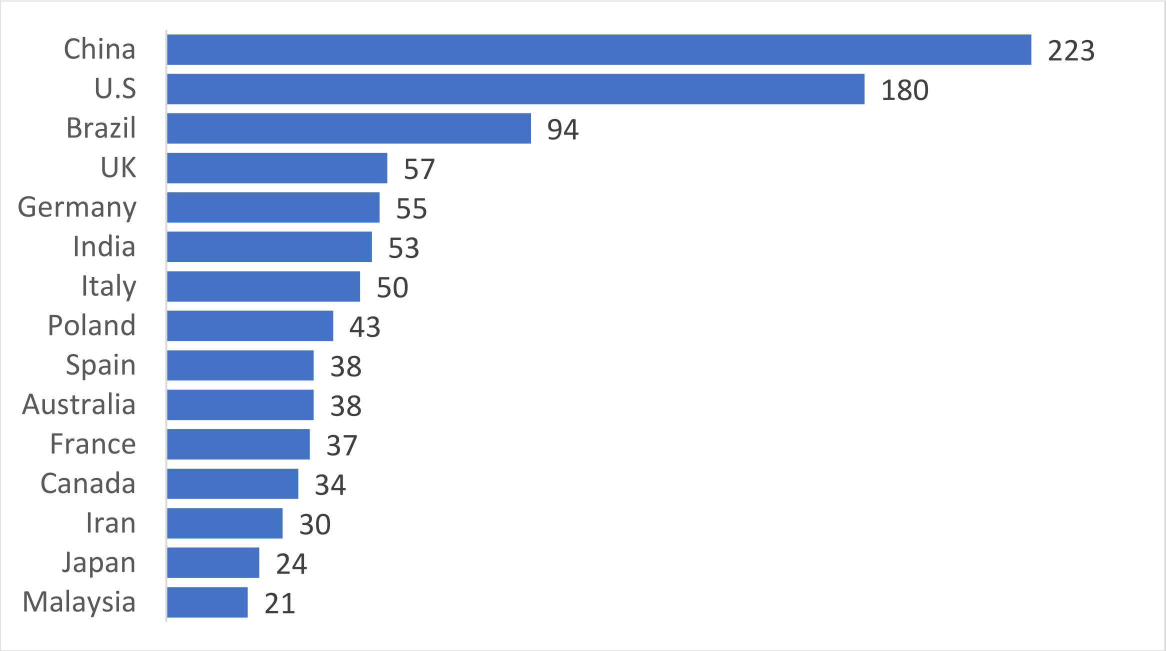


Figure 4 - Number of retrieved publications per country.

The analysis highlights the top 10 pertinent areas. Agricultural and Biological Sciences lead with 28% of publications, followed by Engineering at 11.1% and Environmental Science at 9%. Together, the three areas constitute nearly half of the articles, encompassing 48.1% of all published content. The research area in Agricultural and Biological Sciences has played a pivotal role in advancing the corresponding knowledge. Figure 5 depicts publications per area.

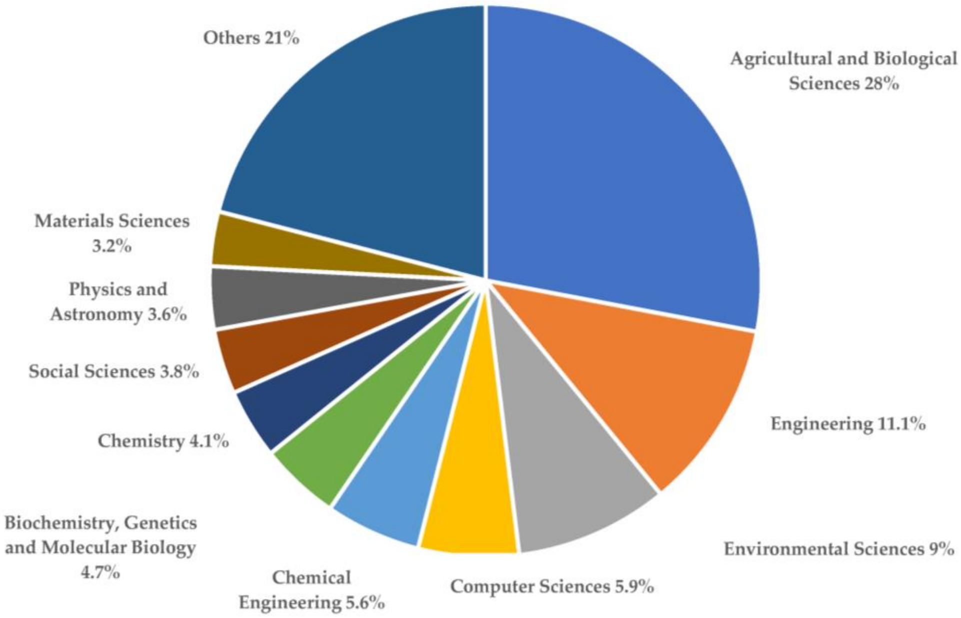


Figure 5 – Number of retrieved publications per area.

A Word cloud analysis provides a comprehensive view of the key areas in the field, revealing complex interconnections between technology, agriculture, and food safety amid global challenges like climate change. Figure 6 depicts the word cloud.

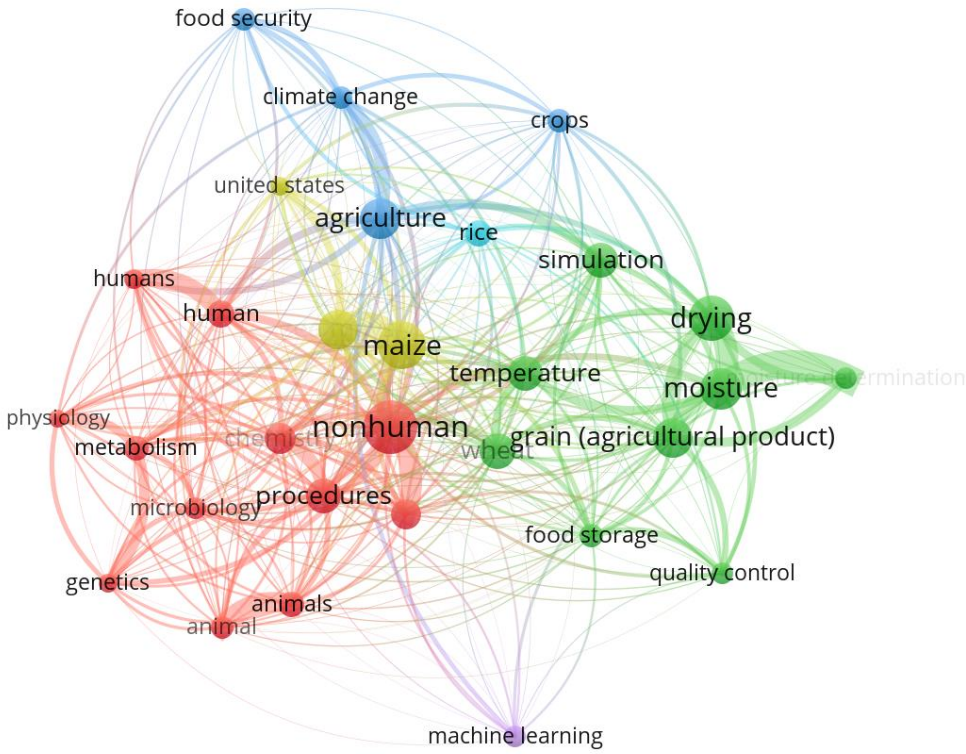


Figure 6 – Word cloud regarding retrieved publications.

The analysis regards six groups:

1. Digital Technologies and Sustainable Agriculture: keywords like “agriculture,” “plantations,” and “quality control” emphasize the relevance of digital technologies in optimizing agricultural processes for greater efficiency and sustainability in production and post-grain harvest.
2. Accurate Monitoring and Grain Quality: Terms such as “temperature,” “humidity,” “quality control,” and “artificial intelligence” underscore the importance of rigorous monitoring in storage and post-harvest conditions. IoT sensors and machine learning techniques improve grain quality, preventing losses and ensuring food safety.
3. Simulation and Climate Change: The words “simulation” and “climate change” highlight the need to anticipate climate impacts on plantations and post-harvest.

Simulation enables the modeling of climate scenarios to develop strategies addressing climate change challenges.

4. Efficiency and Sustainability: “Artificial intelligence,” “machine learning,” and “drying” reflect the pursuit of energy efficiency and sustainability in the post-harvest process. AI-driven automation optimizes drying, reducing resource consumption and ensuring grain quality.
5. Biological Data Integration: Terms like “genetics,” “microbiology,” “metabolism,” and “physiology” indicate the convergence of biology and digital technology. Integrating molecular and biological data enhances our understanding of interactions between grains, microorganisms, and environmental factors.
6. Socioeconomic Challenges and Food safety: Keywords such as “food security” and “human” highlight the importance of grain quality for global food safety. Post-harvest digital technology impacts agricultural production, human health, and nutrition.

The word cloud analysis reveals that digital technologies in grain post-harvest encompass agricultural, environmental, biological, economic, and social aspects. Integrating these elements is essential to address challenges like climate change and the global demand for quality food. Finally, Figure 7 depicts publications per digital technology.

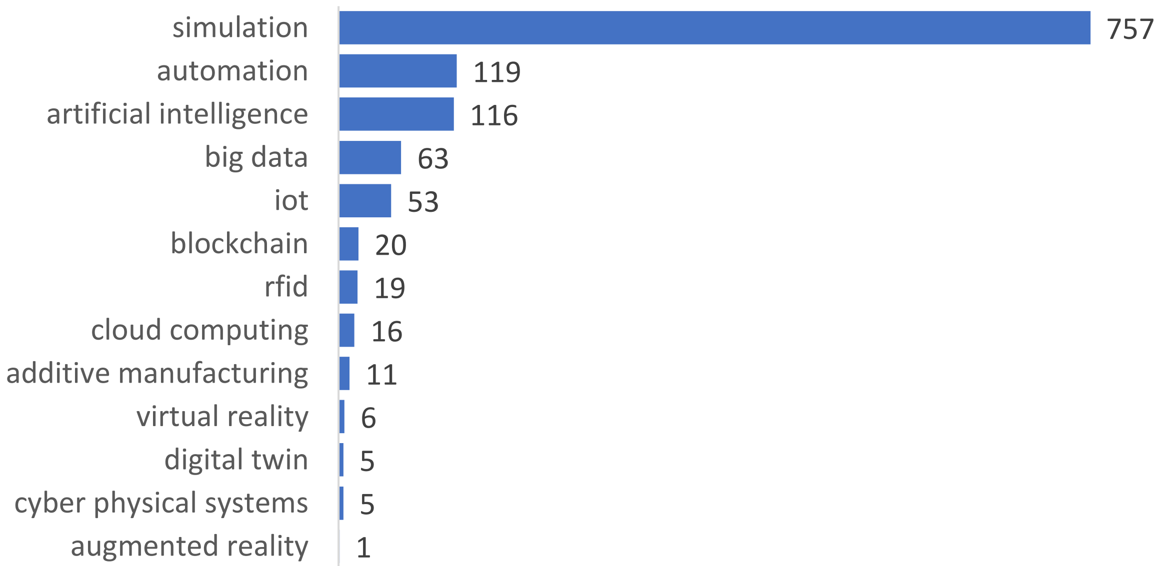


Figure 7 - Number of retrieved publications per technology.

## 3.2 Descriptive Analysis: Technologies

Out of the 963 articles, 129 deal with 2 or more digital technologies simultaneously, with 78, 27, 11, 8, 2, 2, and 1 article covering 2, 3, 4, 5, 6, 7, and 10 technologies, respectively. Nonetheless, this study focuses on one technology at a time, identifying the article with the highest number of citations that handles the targeted technology. Simulation is the most prevalent, followed by automation and artificial intelligence. On the other extreme, virtual reality, digital twin, cyber-physical systems, and augmented reality constituted topics with minimal scientific research in this bibliometric review. The dominance of simulation, automation, and artificial intelligence systems underscores their significance in developing new post-harvest technologies, positively impacting the digital transformation of the segment. Gaps exist for virtual reality, digital twin, cyber-physical systems, and augmented reality, necessitating ongoing research for technological advancements in the sector. Table 2 displays the most cited article by technology as well as the citation numbers in July/2023 in the Scopus database.

| Technology | Author of article | Cites in July/ 2023 | Cites per year |
|---|---|---|---|
| Simulation (SIM) | Paterson and Lima (2022) | **389** | 389 |
| Automation (AUT) | Fatima et al. (2020) | **102** | 34 |
| Artificial intelligence (IA) | Granato et al. (2018) | **303** | 60,6 |
| Big data and cloud computation | Sharma et al. (2020) | **161** | 53,7 |
| IoT | Pranto et al. (2021) | **55** | 27,5 |
| Blockchain | Cattaneo et al. (2021). | **64** | 32 |
| Rfid | Visconti et al. (2020) | **40** | 13,3 |
| Additive manufacturing (AM) | Lin et al. (2019) | **12** | 3 |
| Virtual reality (VR) | Duan et al. (2019) | **12** | 3 |
| Digital twins | Kim and Lee (2022). | **01** | 1 |
| Cyber-physical systems (CPS) | Iftekhar et al. (2021) | **21** | 10,5 |
| Augmented reality (AR) | Chen et al. (2022) | **02** | 2 |

Table 2 – Most cited article for each technology.

In the table, two technologies exhibit low citation rates. Nevertheless, scholarly discourse posits that digital twins [37] and augmented reality [38] hold potential relevance in the domain of machine manufacturing, which is an indispensable facet of grain post-harvest activities management. Consequently, despite the modest citation frequencies, both technologies persist as focal points within this study.

Regarding simulation, the study addresses the impact of climate change on mycotoxins in food, emphasizing the significant influence of climate change on mycotoxins. Temperature and water activity crucially affect mycotoxigenic fungi and mycotoxin production. The study notes that fungal crop diseases serve as relevant indicators for mycotoxin contamination even pre-harvest. Additionally, mycotoxin production can occur in various post-harvest scenarios. It emphasizes regional variations in the impact of climate change, indicating that countries with cold or temperate climates may become more susceptible to aflatoxins as temperatures rise. In contrast, tropical countries may face challenges related to the extinction of thermotolerant fungi like Aspergillus flavus. Cold regions may encounter issues associated with toxins such as ochratoxin A, patulin, and Fusarium toxins. However, regions with controlled storage facilities might mitigate post-harvest storage problems at an extra cost. The study highlights the need for more awareness regarding mycotoxins and their connection to climate change in some non-European countries. In conclusion, the article asserts that climate change significantly impacts mycotoxins in food, influencing both pre-harvest production and post-harvest storage, with specific implications for various regions and mycotoxin types. Moreover, awareness of these issues varies among countries, posing increasing future challenges for mycotoxicologists [25].

Regarding automation, the article highlights the intrinsic connection between the growth and development of cereal crops and climatic factors like temperature, day length, and increasing-degree days. These crops prove highly sensitive to specific seasonal environments. Global temperatures rise, attributed to fossil fuel combustion and deforestation, and disrupt crop growth and development, notably impacting the phenological development of plants and consequently affecting economic crop production. Scientists and farmers adapt to climate-induced phenological changes by adjusting their sowing times and selecting cultivars aligned with temperature and climate shifts. Given the inevitability of global climate warming, adaptation becomes imperative for ensuring food safety, particularly in cereal production. Enhancing food safety involves more efficient agronomic management, developing climate-adapted genotypes, and increasing genetic biodiversity. These strategies help alleviate climate warming effects on cereal crops. The article delves into the detailed impact of climate warming on phenological changes and the adaptive measures for various cereal crops. It provides an overview of the management strategies addressing challenges posed by global warming. In conclusion, the article asserts that climate warming significantly affects cereal crop growth and development, prompting scientists and farmers to adopt diverse strategies for adaptation. Food safety can be sustained or improved through actions such as adjustments in agronomic management, the development of climate-resistant varieties, and the promotion of genetic biodiversity [26].

Regarding artificial intelligence, multivariate statistical techniques derived from analytical chemistry are widely used in food science and technology for managing large and intricate datasets encompassing multiple samples, types, and responses. Chemometrics finds applications in geographic origin authentication, tamper tracking, and agricultural systems analysis, ensuring the authenticity and quality of high-value-added commodities. The application of chemometric tools in food science studies involves studying the impact of process variables on chemical composition and food authentication based on chemical markers. Principal component analysis and cluster analysis associate levels of bioactive components with in vitro functional properties, while supervised multivariate statistical methods are employed for authentication. Chemometrics proves instrumental in addressing complex real-life problems, providing a holistic context for multifactorial challenges. It underscores the benefits for government bodies and industries in monitoring food, raw materials, and processes with high-dimensional data. The study emphasizes the importance of selecting statistical approaches for analyzing complex and multivariate data. The discussion includes practical examples and a review of the pros and cons of commonly used chemometric tools. In conclusion, chemometrics plays a crucial role in food science, aiding in the analysis of complex data, product authentication, and understanding the effects of process variables on chemical composition. It is a valuable tool for addressing multifactorial challenges in a holistic context, especially relevant for monitoring food and raw material quality, with the choice of appropriate tools essential for effective analysis [27].

Regarding Big Data and cloud computing, the article addresses challenges faced by agrifood supply chains (FSCs) during the COVID-19 pandemic. FSCs encountered unprecedented risks, emphasizing the need to comprehend and address these challenges. The study aims to investigate post-pandemic risks on FSCs and propose strategies for creating resilient organizations. It utilizes the Fuzzy Linguistic Quantifier Order Weighted Aggregation (FLQ-OWA) methodology to assess these threats, revealing significant impacts on FSCs. Identified risks include supply, demand, financial, logistical and infrastructure, management and operational, political and regulatory, as well as biological and environmental risks. The impact varies depending on the organization’s scope and scale. Based on the results, the article suggests strategies to enhance FSC resilience, such as adopting Industry 4.0 technologies, promoting supply chain collaboration, and sharing responsibility among chain participants. The study offers theoretical and managerial implications, providing insights into supply chain management theory and practical strategies for professionals. In summary, FSCs encounter unprecedented challenges due to the COVID-19 pandemic. Identifying, assessing, and managing risks are crucial for building resilient organizations. The study underscores the significance of addressing various risks, from supply and demand to financial, logistical, and regulatory factors. Strategies like adopting advanced technologies and promoting supply chain collaboration are recommended for ensuring a sustainable future for FSCs [28].

Regarding the IoT, the agricultural sector lags in adopting recent technologies, with traditional methodologies persisting in pre- and post-harvest processing. This results in issues such as inadequate payment for farmers, a lack of consumer information, and increased intermediary prices. The proposal advocates for technologies like blockchain, smart contracts, and IoT devices to modernize agriculture. These technologies automate processes, build trust between parties, and enhance efficiency in pre- and post-harvest segments. Various aspects of blockchains, smart contracts, and IoT devices can be employed in agriculture’s pre- and post-harvest phases. The proposed system uses a blockchain as a base, with IoT devices collecting field data and smart contracts regulating interactions. Implementation details, diagrams, explanations, and associated gas costs are provided for a better cost understanding. System analysis covers challenges and advantages, emphasizing blockchain's positive traits—immutability, transparency, and robust security. The research concludes that adopting technologies like blockchain, smart contracts, and IoT devices can modernize agriculture, addressing transparency issues, insufficient farmer payments, and rising intermediary prices. It underscores the transformative potential of combining blockchains, smart contracts, and the IoT in agriculture [29].

Regarding blockchains, the article notes a political consensus on reducing food losses and waste (FLW) importance but identifies significant information gaps. Summarizing recent research filling these gaps, it aims for a more comprehensive understanding of challenges and opportunities. Five crucial challenges for researchers, policymakers, and practitioners in FLW reduction are highlighted. The first is accurately measuring and monitoring FLW, quantifying and tracking its extent. The second involves evaluating the costs and benefits and understanding the associated trade-offs. The third is developing effective policies and interventions, even with limited information. The fourth is considering value chain interactions and understanding their impact on FLW reduction efforts. The fifth challenge involves income transitions and economic development, predicting their effect on food losses and waste. In conclusion, despite recognizing the need to reduce FLW, information gaps persist. The article identifies five key challenges for more effective and informed FLW reduction strategies, covering measurement, evaluation, policy design, complexities in the food value chain, and developing economies [30].

Regarding RFID, the article highlights the transformative impact of modern IoT-oriented technologies on various human activities, including agriculture. These technologies optimize production processes, enhancing water- and fertilizer-use efficiency and improving crop quality and productivity. It details the development of an intelligent RFID-based agricultural traceability and management system that adjusts irrigation and fertigation operations based on factors like crop type, growth phase, soil parameters, environment, and meteorological information. A software architecture aids in the system's decision-making process, and data collected in the field is transmitted via a solar-powered wireless sensor network (WSN). The solar energy supply system and optimized programming result in long WSN node autonomy, reducing the need for maintenance. In addition to the agricultural management system, the article explores RFID in agrifood product traceability, presenting a Bluetooth Low Energy (BLE) sensor tag design to monitor parameters indicative of failure or deterioration in the supply chain. A mobile application is developed for monitoring tracking information and product storage conditions. The general conclusion is that RFID application in agriculture significantly improves the sector, enabling more efficient monitoring of agricultural operations and agrifood products along the entire supply chain [31].

Regarding additive manufacturing, the article addresses the development of machine vision-based technologies aiming to replace human work in quickly and accurately detecting the quality of agricultural products, particularly the appearance quality of dry soybean seeds after harvest. It describes the low-level representation of the JMBoF framework used for inspecting the quality of dry soybean seeds, involving accelerated robust feature extraction and spatial layout of Lab* color features. Two feature categories characterize dry soybean seeds, and Bag-of-Feature models generate visual dictionary descriptors. The low-rank representation method eliminates redundant information, and a multi-class support vector machine algorithm classifies the low-rank representation of the multimodal bundle of features. The JMBoF classification algorithm is validated using a dataset of soybean seed images, showing a significant improvement over the state-of-the-art single-modal bag approach. The article suggests that the developed method plays a valuable role in the classification procedure of dry soybean seeds after harvest, contributing as an important technology. The conclusion is that the application of machine vision technologies in agriculture, specifically in the quality inspection of dry soybean seeds, is being explored innovatively. Using the JMBoF framework, visual dictionary descriptors, the LRR method, and advanced classification algorithms shows promising results in soybean seed quality classification and detection, outperforming previous approaches, with significant implications for the post-harvest classification process of soybean seeds [32].

Regarding virtual reality, the article emphasizes the significance of food safety in the economy and people’s lives within the context of virtual reality. The accurate monitoring of environmental parameters, particularly barn temperature, is proposed for creating an optimal food storage environment. The study involves collecting grain temperature data over 423 days in a real barn and obtaining corresponding meteorological data from the China Meteorological Data Network. Machine learning algorithms, specifically those that support vector regression (SVR) and adaptive boosting (AdaBoost), are employed to predict the average grain pile temperature. Different kernel functions are integrated into the SVR model, and a suitable base estimator and several estimators are selected for the AdaBoost model to optimize prediction results. Pearson's correlation coefficient analyzes historical barn data and weather forecast data, while principal component analysis (PCA) reduces data size, eliminating redundant information. Results indicate that these approaches accurately predict grain pile temperature, with the PCA-enhanced AdaBoost method outperforming others. In conclusion, utilizing machine learning algorithms, including SVR and AdaBoost, alongside meteorological data enables precise predictions of grain pile temperature, enhancing food safety by optimizing food storage conditions. PCA-driven dimension reduction further improves model performance [33].

Regarding digital twins, the article addresses challenges in post-harvest grain logistics, where exposure to unprotected environments during transport and storage can degrade grain quality due to factors like insects, pests, rancidity, and discoloration. The proposed solution involves adopting a containerized grain logistics approach, utilizing conservation containers to ensure protected environments during logistical processes. This approach maintains grain quality and identity throughout transportation and storage, offering a viable solution for mitigating quality deterioration. Cost comparisons between containerized and conventional bulk logistics consider shipping, storage, tariffs, and infrastructure costs. Conventional bulk logistics excel in maritime transport and storage costs, while containerized logistics prove economically viable in terms of tariff and infrastructure costs. The adoption of containerized grain logistics is discussed for their potential to improve sustainability by tracking and preserving grain longer in protected environments. In conclusion, containerized grain logistics emerge as a promising approach to counter grain quality deterioration during post-harvest logistics, with favorable economic aspects contributing to quality preservation and sustainability in the grain supply chain [34].

Regarding cyber-physical systems, the article explores the integration of blockchains and the Internet of Things (IoT) in cyber-physical systems for applications in supply chain management, healthcare, and finance. It emphasizes the IoT's role in data collection and utilizes the Hyperledger Fabric blockchain platform to demonstrate access control and establish the root of trust for IoT devices. Furthermore, the study implements an attribute-based access control (ABAC) mechanism using Hyperledger Fabric components to control access to IoT devices. The Raspberry Pi 4 Model B, relying on the ARM64 architecture, serves as an IoT device, and the study successfully generates executable binaries and custom Docker images from the Hyperledger Fabric source code for this architecture. Testing on the IoT device confirms the effectiveness of the blockchain–IoT integration and access control mechanism on the ARM64 architecture. The conclusion asserts that integrating the Hyperledger Fabric blockchain with IoT devices, like the Raspberry Pi 4 Model B, is both feasible and effective. The study demonstrates the use of the attribute-based access control mechanism for providing security and access control to IoT devices in various applications. The custom generation of executable binaries and Docker images for different architectures underscores the adaptability of the proposed solution [35].

Regarding augmented reality, the introduction of technology has significantly increased research and applications in various sectors, including the infrastructure construction industry. Despite interest in this area, there needs to be more quantitative analysis and comprehensive evaluation of study results, indicating a need for a more thorough understanding. The study employs CiteSpace software version 5.7.R2 to analyze the relevant literature found in the Web of Science database from 2007 to 2022 and address the gap. This analysis maps research development at the intersection of Big Data and the construction industry. Using CiteSpace, the study conducts quantitative and qualitative analyses to comprehend the knowledge base, research focal points, and emerging trends in this field. The findings reveal that Chinese and American researchers have published relevant articles in international journals, with well-known universities in these countries forming the main group of research institutions. Research focus points include Building Information Modeling (BIM), data mining, energy savings in buildings, smart cities, and disaster and damage prevention. The article suggests a future increase in research connecting the construction industry with emerging technologies such as Big Data, BIM, and cloud computing. It provides a preliminary overview of Big Data research in the construction field, classifies and analyzes existing results, highlights focus areas, and suggests future directions. In conclusion, there is growing interest and research at the intersection of Big Data and the construction industry. Quantitative and qualitative analyses by CiteSpace software identify research trends, leading institutions, and hot topics, contributing to a deeper understanding of the development and emphasis areas in this evolving field [36].

# 4 MANAGING LOSSES WITH TECHNOLOGICAL SOLUTIONS: APPLICATIONS AND GAPS

The bibliometric analysis indicates a substantial surge in interest in applying advanced technologies in FSCs. Approaches range from deploying machine learning algorithms for grain quality inspection to implementing intelligent monitoring and traceability systems. These technologies carry the potential to diminish post-harvest losses and enhance quality, efficiency, safety, and sustainability in grain storage and transportation. Technological solutions ensure the quality and safety of food products, addressing concerns such as mycotoxin detection, environmental parameter monitoring, and traceability.

Understanding technology’s importance involves pinpointing the most vulnerable points to losses in the post-harvest process. A previous study [23] identifies and critically analyzes, including visual resources, the nine critical control points (CCP) for post-harvest losses that are used in this study. The process begins with grain reception (CCP1) and unloading into hoppers (CCP2). Pre-cleaning (CCP3) eliminates coarse impurities before transferring grains to buffer silos (CCP4) for intermediate storage. If necessary, grains undergo treatment in dryers (CCP5) for high-temperature treatment, eliminating moisture for safe, prolonged storage. Cleaning machines (CCP6) remove fine impurities affecting quality. Subsequently, grains are stored in permanent silos (CCP7) until they are ready for sale. After the sale, the shipping process begins (CCP8). Various connection points (CCP9) contribute to losses during storage. Implementing digital technologies can significantly reduce losses throughout the entire process [23].

Three experts from Brazilian companies specializing in technical and engineered solutions, integrating various technologies, were consulted to determine the most suitable technology for each CCP. The analysis goes from the early project stages to technical assistance, passing by operational issues, including a research gap for future developments.

Augmented reality (1), virtual reality (2), and simulation systems (3) contribute to the development phase of equipment and technologies by industry engineers addressing post-harvest solutions. Simulation contributes more to correctly dimensioning storage unit flows, encompassing validation, operational training, and preventive/predictive maintenance during storage operations. The main research gap is to extend the employment of augmented reality and virtual reality to a larger number of applications in equipment design, which is attested by the low citation rate of both.

Automation (4) operates individually in each equipment and process, enabling the autonomous, safe, efficient, and sustainable execution of intended processes. At an advanced level, it integrates different equipment in a production unit through an automation network of flow routes. Communication protocols, steering valves, and automated records, integrated into a supervision system, facilitate information exchange among equipment, forming a collaborative network. The main research gap lies in enhancing the speed and reliability of data exchange among remote systems, enabling the remote and non-human operation of silos and conveyors.

Strategically placed sensors at each process stage monitor machine conditions and characteristics related to processed and stored grain quality. The information gathered by sensors, integrated into equipment automation logic, becomes valuable data for artificial intelligence (5) and Internet of Things (IoT) (6) systems. These systems either operate directly on devices, employing edge computing for quick responses, or rely on cloud computational AI systems connected to a Big Data infrastructure (7). This context provides variables for cloud-based digital twins (8), feeding field equipment with optimal operating parameters retrieved from simulation runs (3) for autonomous decision making. All connected to a platform, this setup forms a cyber-physical system (9), playing a pivotal role in introducing new products and serving various stakeholders. The platform also manages traceability throughout the entire post-harvest grain journey, integrating blockchains (10) to track products to end consumers. Finally, each trans-shipment may be supervised by RFID systems (11), which also contribute to inventory management and tax control. The main research gap lies in enhancing the reliability of critical equipment as well as in more flexible and modular interfaces, which would reduce implementation costs and accelerate the time to the completion of projects.

Regarding technical assistance, several components responsible for grain flow in a storage unit undergo premature wear during operation and can be swiftly replaced during harvest. Additive manufacturing (12) is a promising alternative, offering rapid component replacement without extensive supply chain involvement, including not only machinery but also buildings. As in augmented reality and virtual reality, the main research gap is to extend the use to a larger number of applications in equipment design, which is also attested by the low citation rate.

Table 3 synthesizes the most influential technology concerning CCPs. The last row encompasses examples of a case study involving the technology in various types of post-harvesting activities.

| Critical Control Points - PCC | Augmented Reality (1) | Virtual Reality (2) | Simulation (3) | Automation (4) | Artificial Intelligence (5) | IoT (6) | Big Data/CC (7) | Digital Twins (8) | Cyber-Physical Systems (9) | Blockchain (10) | Rfid (11) | Additive Manufacturing (12) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CCP 1—Grain reception | X | X | | X | | X | X | | | X | X | X |
| CCP 2—Hoppers | X | X | | X | | | | | | | | X |
| CCP 3—Pre-cleaning | X | X | X | X | X | X | X | X | X | X | | X |
| CCP 4—Buffer silos | X | X | | X | | | | | | | | X |
| CCP 5—Dryers | X | X | X | X | X | X | X | X | X | X | | X |
| CCP 6—Cleaning machines | X | X | X | X | X | X | X | X | X | X | | X |
| CCP 7—Storage silos | X | X | X | X | X | X | X | X | X | X | | X |
| CCP 8—Shipping | X | X | | X | | X | X | | | X | X | X |
| CCP 9—Connection points | X | X | | X | | | | | | | | X |
| Example of a recent case study | [37] | [37] | [38] | [39] | [40] | [41] | [42] | [43] | [44] | [45] | [46] | [47] |

Table 4 – Relationship between technological solutions and critical control points.

The review emphasizes the significance of real-time data collection and analysis for supporting post-harvest decision making. Challenges like the absence or low accuracy of data, low-speed exchanging, and interoperability between technological systems demand specific approaches. Technologies stand for their potential to enhance natural resource-use efficiency, reduce waste, and improve sustainability. However, a lack of clear standards and integration protocols can impede the widespread adoption and effective interconnection of technologies. Furthermore, ethical and privacy concerns related to data collection and sharing are addressed to a limited extent.

Specific challenges persist in grain post-harvest due to grain heterogeneity, environmental variations, and storage diversity. The application of technologies faces difficulties, emphasizing the crucial need for reliable and accurate detection and inspection methods to prevent losses and ensure quality. Large-scale technology implementation, especially in traditional agricultural settings, may encounter resistance owing to cultural barriers, insufficient training, and limited resources.

Research gaps in post-harvest grain management involve the development of specific approaches for different grain types and storage environments. In-depth studies addressing the adaptation of technologies to natural variability and diverse conditions still need to be included. Additionally, cost–benefit analyses at various scales and the economic and social implications of post-harvest technologies often need to be included in research. Simulation, automation, and artificial intelligence systems are deemed crucial, showcasing their fundamental role in advancing post-harvest technologies and promoting positive digital transformations. However, gaps in virtual reality, digital twins, cyber-physical systems, and augmented reality domains call for continuous investigations to drive technological progress. In summary, the application of post-harvest grain technologies holds promise for improving efficiency and quality but encounters significant challenges. Collaboration among researchers, industry stakeholders, and farmers is critical for developing practical, scalable, and culturally sensitive solutions. Future research should address technology adaptation, comprehensive cost–benefit analysis, and social impact, seeking integrated solutions to enhance post-harvest grain management.

## 5 FINAL REMARKS

The purpose of this article was to establish a connection between digital technologies employed in Food Supply Chains (FSCs) and critical control points within post-harvest management systems. The research methodology was a combination of a bibliometric analysis, a comprehensive review of the recent literature, and an analysis from experts in the industry. The literature review identified and examined 12 contemporary digital technologies that are currently being applied in post-harvest systems. Additionally, a recent study pinpointed nine critical points within post-harvest systems that contribute to losses and necessitate effective control measures. The primary contribution of this article lies in presenting a categorized list of the most influential technologies corresponding to each identified control point. A table has been created to illustrate the relationships visually. The significance and novelty of this study lie in providing managers and practitioners in companies specializing in engineering solutions for post-harvest systems with a practical guide for decision making in the selection of technologies for future projects, ultimately aiding in optimizing post-harvest processes, minimizing losses, and reducing environmental impact.

The examination of digital technologies employed in grain post-harvest underscores their significance in optimizing processes related to grain storage, monitoring, and quality. Analyzing consistent patterns reveals technological trends, practical implications, and future challenges for implementing these technologies. Key digital technologies include IoT sensors, real-time data analytics, machine learning, and automation, which have significantly transformed the post-harvest grain sector. The real-time monitoring of critical environmental conditions, such as temperature, humidity, and air quality, empowers producers and operators to pinpoint critical points, prevent losses, and make informed decisions for preserving grain quality.

Despite the advancements in digital solutions, challenges emerge that necessitate attention. Addressing issues such as interoperability among different systems and devices, the reliability of critical equipment, the cybersecurity of collected data, and the training of professionals to operate and interpret these technologies requires strategic approaches. However, the accessibility and adoption of these solutions in diverse agricultural contexts may vary, underscoring the importance of considering socioeconomic and regional factors.

This study paves the way for future research avenues and highlights opportunities for managers and practitioners in the industry.

One potential research focus is exploring methods to foster collaboration among agricultural experts, software engineers, data scientists, and public policymakers to promote the use of technology in reducing post-harvest losses. In this context, it becomes important to investigate how to enhance and cultivate relationships within networks of small and medium enterprises, particularly within the agro-industrial sector in southern Brazil [48]. Facilitating access to technology for these companies holds the potential to improve efficiency and sustainability within the FSC.

Another avenue involves developing longitudinal case studies, tracking data over time, and comparing post-harvest system performances before and after the implementation of technological solutions. Lastly, in line with the study's framework, a suggested survey involves assessing rural producers in specific regions, such as the northwest of Rio Grande do Sul, the southernmost state in Brazil, or Mato Grosso, a state in the central-western region of Brazil—areas characterized by intense grain production. This survey aims to investigate the application degree, intensity, and perceived importance of each technology mentioned by rural producers. By employing structural equation analysis and comparing it with the enterprise's profitability and environmental footprint, it becomes feasible to identify which technologies can contribute to the producer's final economic and environmental performance.

In terms of practitioners, this study presents an integrated framework designed to assist engineering developers and systems designers in prioritizing innovative solutions for existing challenges. Additionally, it provides operations managers with a fresh perspective on incorporating new technologies for expanding operations further. New perspectives should involve the utilization of remote, non-human operators and advanced algorithms to streamline routine decision-making processes.

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# 4 SECOND ARTICLE - OPPORTUNITIES OF DIGITAL TRANSFORMATION IN POST-HARVEST ACTIVITIES: A SINGLE CASE STUDY OF AN ENGINEERING SOLUTIONS PROVIDER

## ABSTRACT

The purpose of this article is to identify opportunities that digital transformation in post-harvest activities offers to an engineering solution provider. The research method is a simple case study. The object is a company based in southern Brazil that provides engineering-integrated digital solutions to grain producers, including products and services. The specific objectives are to describe the company's digital products and services, identify opportunities and players, and discuss how players can take advantage of opportunities owing to business process digitalization. The main results include separating products into three technological layers, identifying five types of opportunities (financing, commercialization, operation, logistics, traceability, and insurance), eight types of players, and the main opportunities for each player. The most significant opportunities are risk reduction in insurance contracts, improvement in grain quality, increments in food safety, and accurate information on grain movements. The main implication of the study is that grain producers and other players can explore opportunities, and solution providers can evolve toward complete digitalization by integrating service into the current offerings of post-harvest engineering solutions.

Keywords: digital transformation; agribusiness; post-harvest; food safety; food quality; engineering solutions.

## 1 INTRODUCTION

The world population should rise from 6.9 billion in 2010 to more than 9.4 billion in 2050 [1]. At the same time the population grows, the global availability of arable land per capita decreases. While in 1950 there were approximately 0.52 hectares per capita, by 2050, this figure will decrease to 0.17 hectares [2]. Furthermore, aggravated by climate change, the per capita demand for water has also risen, completing a picture, and highlighting the need for more productivity in agricultural production systems [3]. The use of digital technologies can contribute to increasing such productivity [4]. The literature offers many cases in developed and developing countries that support the success of digital transformation in agri-food system management [5].

Agriculture, specifically the production of grains and cereals, plays an essential role in producing food for human and animal consumption. The literature estimates that 1 kg of beef, pork, and poultry production requires 7, 4, and 2 kg of grains, respectively [6]. The interest of this article includes the so-called grain post-harvest activities.

Post-harvest activities include companies from the metal-mechanical industry that provide engineering solutions for the sector. Such companies deliver solutions to maintain the quality of grains or cereals after harvesting until used by the agroindustry, retailers, and final consumers [7]. For vendors of post-harvest supporting equipment, digital trans-formation is an opportunity for a rapid evolution in business models. The income of such companies has depended almost exclusively on the sale of physical goods, such as grain silos, conveyors, storage facilities, or dryers. Currently, those companies, based on digital technologies, also offer engineering solutions that incorporate services into the current portfolio of products [8]. Nonetheless, such companies should still understand how digital transformation influences their business models. It is necessary to identify what capabilities to develop as well as the main opportunities digital transformation may convey to provide new sources of revenue [9]. Identifying such opportunities is the research gap this article aims to bridge.

The purpose of this article is to identify opportunities that digital transformation in post-harvest activities offers to an engineering solution provider. The research method is a simple case study. The object is a company based in southern Brazil that provides engineering-integrated digital solutions to grain producers, integrating products and services. The specific objectives are to describe the company's digital products and services, identify the main types of opportunities, the interested players, and discuss how players can benefit from opportunities. The main expected implication is to offer post-harvest solutions vendors a guideline to explore new opportunities and change their business models by integrating digital services and physical goods. The structure of the rest of the article is as follows. Sections 2 to 5 contain the literature review, methodology and results, types of opportunities, and final remarks.

## 2 LITERATURE REVIEW

### 2.1 Digital Technologies

Cutting-edge digital technologies merge information, computing, communication, and connectivity to disrupt business models [10] and reshape relationships within business networks [11]. The key characteristic of digital technologies lies in their ability to integrate digital capabilities into objects that were previously purely physical, like equipment, appliances, or vehicles [12]. Furthermore, digital technologies introduce advanced functionalities, such as autonomy and tracking capabilities, which drastically enhance performance [13]. In essence, digital innovation initiatives blend digital and physical elements within a layered modular architecture, yielding novel products accompanied by unprecedented services that cater to the end user's needs [14]. Such initiatives often lead to profound alterations in products [15], organizational structures, and process management [16]. Ultimately, a sociotechnical digital transformation unfolds in social and institutional contexts, rendering digital technologies integral to the infrastructure [17].

Digital innovation possesses distinctive traits, including re-programmability, data homogenization, and a self-referential nature. Layered modular architectures form the organizing logic behind digitized products, allowing them to function simultaneously as both products and platforms. An exemplary instance appears in devices reliant on cloud storage. The layered architecture empowers companies to compete in specific layers, such as equipment, while fostering collaboration in others, such as services [18], aligning with the established concept of coopetition [19]. The convergence of digital technologies is ap-parent through interconnected yet distinct elements like artifacts, platforms, software, and databases that leverage the same digital infrastructure [14].

By embedding digital artifacts into physical devices, information can be stored, enabling programmability, addressability, communication, traceability, and association [20]. The separation of form and function enables artifacts to swiftly acquire new features at relatively insignificant costs. Digital infrastructures, such as social media, data analytics, cloud computing, and 3D printing, offer tools for rapid scalability [21] and international expansion [22]. In recent years, trailblazing pioneers like Google, Amazon, and Meta have risen to prominence, spearheading a new era of platform-based competition [23,24].

Prominent digital companies and their platforms have expedited the process of digitalization in the business realm. A seminal article from 1991 [25] introduced the concept of a pervasive computing environment, envisioning a future where revolutionary technologies seamlessly blend into everyday life, becoming indistinguishable from commonplace activities like reading a book. A decade later, a pivotal study [26] predicted the proliferation of ubiquitous computing as mobile computing merged with pervasive computing, which integrates natural movements and interactions within physical and social environments. Subsequently, digitalization emerged as the foundation for immersive experiential computing, recognized as a sociotechnical process [17]. This process leverages advancements in digital infrastructures to analyze, interpret, and shape transformations within social and institutional contexts. In essence, digitalization is increasingly regarded as an entrepreneurial journey, wherein new business models undermine existing advantages, giving rise to more valuable or rapidly growing companies [14,15,18,20,21].

## 2.2 Digital Transformation in Companies

Digital transformation serves as a catalyst for companies to engage in experimentation and develop new business models [27]. Its impact can be far-reaching, transforming entire industries (e.g., passenger transport, accommodation), unifying products and ser-vices (books, document copying), spawning new businesses (cargo tracking), or presenting novel value propositions (e-commerce offering speed, affordability, and personalized de-livery) [28]. In certain traditional sectors, digital transformation becomes imperative to safeguard established advantages [29-31]. It differs from other forms of strategic evolution primarily due to the rapid pace of change [23,32]. As digital transformation unfolds, it introduces heightened volatility, complexity, and uncertainty, necessitating adjustments in business models, organizational structures, and processes [33-35]. Digitalization opens up opportunities for customer interaction, often leading to unforeseen innovations in business models [36-39].

Organizations equipped with transformative capabilities typically foster agile and entrepreneurial mindsets, emphasizing external networking [40]. Transformative capabilities support strategic renewal processes that involve adapting assets and structures to ensure responsiveness in swiftly changing digital environments [41,42]. Digital transformation presents challenging trade-offs, such as building innovation capabilities while preserving existing products, innovating not only products but also processes, balancing conflicts involving customers, employees, and suppliers, and establishing governance structures that ensure flexibility and control simultaneously [32]. For instance, in e-commerce, buyers and suppliers engage in online commercial transactions [43], creating a wealth of options and new expectations that prompt companies to reassess or augment their transactional value propositions [44-48].

Digital technologies disrupt the traditional logic of business models by elevating customer expectations for complementary products or services [47,49-51]. In response to customer demands, many Internet-based businesses prioritize value creation through exceptional customer service over immediate profit capture, occasionally leading to flawed business models [24]. Consequently, established companies often encounter significant barriers to business model innovation that can impede their journey toward digitalization [29,36,50,52-57].

A business model encompasses a company's mechanisms for creating, delivering, and capturing value [47], encompassing strategic priorities such as cost, revenue, and profit [58]. Innovation-based business models may incorporate elements such as learning [52], shifts in management approaches [59], evolution [60], replication [38], reconfiguration [61], modularization, scalability [62], and digital transformation [36]. Certain business contexts, such as agri-food supply chains, require considerations for sustainability, including eco-design, where the business model targets not only financial performance but also environmental impact [63].

Difficulties in implementing innovation-based models are not uncommon. One rea-son is the belief that standard targets, such as profit margins or revenues, remain stable and can be pursued until achieved. When targets are not met, the common perception is that more effort needs to be invested [64,65]. However, in innovation-driven markets, new alternatives can swiftly disrupt performance parameters, for better or worse, thereby posing risks to even well-established business plans [44,51]. Another challenge arises from the trade-offs that emerge over time between static and dynamic models, necessitating more agile methods and monitoring of additional control variables [56,66]. An illustrative example of a model based on trade-offs is the servitization model, where a product company offers an associated service. Often, to ensure long-term service sales, the product must be sold under less favorable conditions, introducing a trade-off between the product and service [64,67]. This trade-off is commonly observed among providers of post-harvesting engineering solutions. Path dependency represents another barrier to in-novation-based business models, as successful models from the past tend to be perpetuated [68,69]. However, exogenous shocks to performance can help balance the endogenous dependence on models that have previously been effective but are currently approaching exhaustion [70]. Disruptive business models may be deemed unlikely for certain companies [71], as they prefer incremental digitalization over disruptive modifications to existing activities [53,72,73].

The digital transformation of the business model necessitates a convergence of corporate and business unit models, requiring interdependent decision-making [36,56]. To manage strategic complexity, companies often rely on previous experiences rather than entirely new approaches [70]. This decision-making process gives rise to conflicting demands, necessitating a delicate balance between agility and stability [69], certainty and uncertainty [74], or short- and long-term benefits [52]. In some cases, companies adopt a rational approach by addressing challenges in successive stages. They fully overcome one challenge before confronting a contradictory one, as exemplified by product servitization. Once the product-based business model is firmly established (low uncertainty), the company introduces the service component (high uncertainty). Subsequently, the focus may shift back to refining the product and so on, as the process continues.

## 2.3 Enabling Technologies for Digital Transformation in Post-Harvesting Activities

Digital transformation processes must rely on integrating single digital technologies, encompassing the automation of processes and intelligent interconnections of machines. The integration results in cyber-physical systems. Such production systems are simultaneously physical, providing a flow of physical material, and logic, performing supervisory and control tasks [75]. Many recent authors have listed and analyzed the most relevant technologies supporting digital transformation processes, the so-called enabling technologies [76]. Among recent authors, relying on updated references, [77] cite automation (AUT), cyber-physical systems (CPS), big data analysis (BDA), radio frequency identification (RFID), cloud computing (CC), Internet of things (IoT), additive manufacturing (AM), virtual reality and augmented reality (VRAR) and simulation (SIM) as enabling technologies for digital transformation in engineering solutions for primary activities.

Enabling technologies can contribute in different ways to post-harvest engineering solutions. AUT and CSF mainly help to reduce variability in processes [78]. The BDA mainly helps to develop models and find new behavior patterns for key variables in decision making processes. CC mainly helps monitor the physical equipment's life cycle behavior [79]. RFID mainly improves reliability in logistical operations, especially transportation [80]. IoT helps to improve flexibility in key post-harvest processes, such as transportation and warehousing [81]. AM mainly assists in reducing material losses in machinery design and promotes reverse logistics activities, mainly managing shavings and leftovers produced by equipment manufacturers [82]. VRAR helps develop an eco-design and servitization principle: improving the performance of a product by incorporating environmental concerns and associated services [63]. Finally, SIM can help reduce the likelihood of making wrong choices in decision-making processes, including sales and purchases processes [83].

# 3 RESULTS

## 3.1 Methodology

The research strategy was a single case study. The object of study was a Brazilian company that provides engineering solutions for post-harvest activities. The primary re-search technique was non-participant direct observation, in which the researchers directly monitored the main activities in real time without interfering with their results.

The study included the following steps:

(i) The researchers collected and studied related documents issued by the engineering solution provider company.

(ii) The researchers took guided tours of the company's facilities and two nearby customer installations, accompanied by company practitioners.

(iii) The researchers interviewed three portfolio managers of the company.

(iv) In a final meeting, one of the researchers presented the notes to the managers, who eventually amended, adjusted, and finally confirmed the findings, ensuring reliability.

The study does not encompass losses quantification; instead, it solely focuses on de-scribing potential opportunities that may be viable for future innovation initiatives. Owing to the use of a single case study strategy, the findings do not aim at providing external validity, meaning that the findings are only expected to be valid within the research scope. For broader external validity, future research should encompass the entire industry rather than focusing on a single company. The final meeting with the participants, during which they had the opportunity to review and amend certain aspects of the findings, enhances the internal validity and reliability of the study. This research is exploratory and qualitative, representing the initial approach to the problem. Consequently, the results involve descriptive analysis of phenomena without the use of mathematical models to explain them. As is typical of exploratory studies, these findings serve to stimulate further research that can delve deeper into the subject matter.

## 3.2 Post-harvest main activities

Post-harvesting activities play a key role in managing the quality and safety of agricultural grains after the harvesting process. They are responsible for ensuring the integrity of the grains throughout the entire production chain [84]. Grains, being living products, require careful handling and storage, with specific considerations for cleanliness, temperature, humidity, and continuous monitoring [85]. Agricultural grains are prone to rapid deterioration and can be affected by the growth of fungi, yeasts, bacteria, and harmful mycotoxins. Failure to prevent these deterioration processes poses a risk to human consumption, including the consumption of animal products derived from grain-based feeds [86]. One of the key objectives and benefits of post-harvest activities is the loss prevention in the food production system. Various stages of the production cycle can contribute to significant qualitative (in terms of grain quality) and quantitative (in terms of volume) losses during the grain's journey within a grain storage unit (GSU). Figure 1 illustrates the primary issues related to the safety and quality of stored grains.

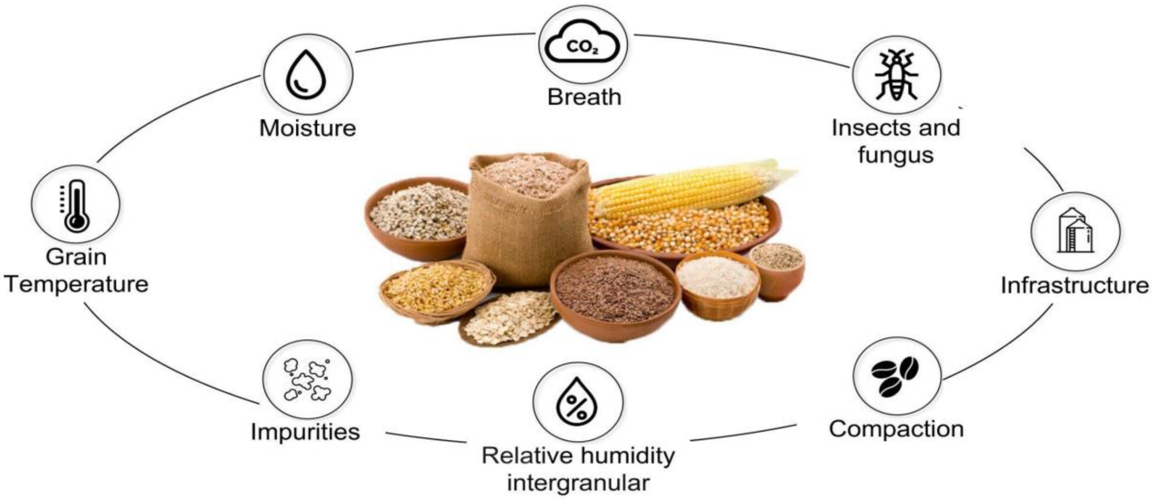


Figure 1. Factors that influence the safety and quality of stored grains.

After the harvest, the grains are transported to a grain storage unit (GSU) using various logistical modes such as road, waterway, or rail transport. In a GSU, there are nine critical control points (CCP) that are crucial for preventing qualitative and quantitative losses in grains. Figure 2 depicts the points. Additionally, Figure 3 highlights a representative GSU equipped by the company under study, highlighting the specific control points.

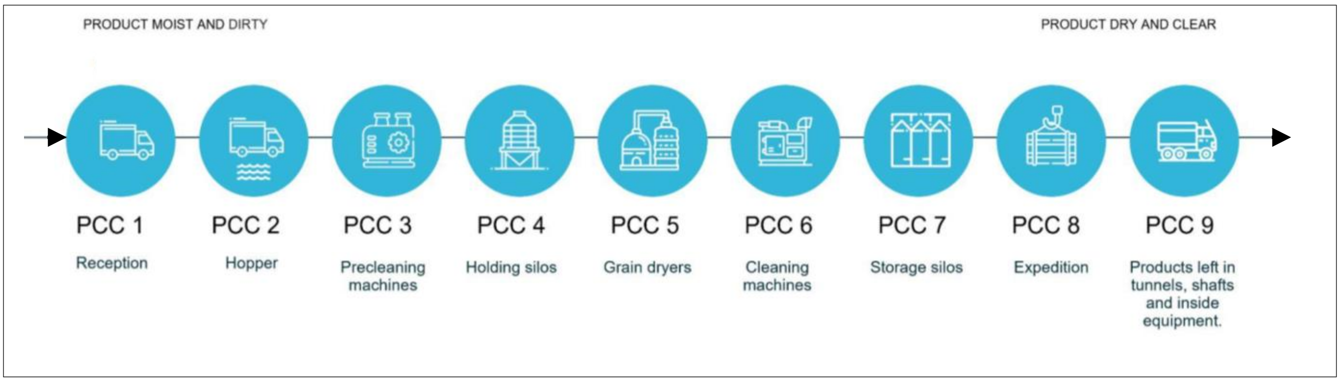


Figure 2. Qualitative and quantitative losses in the post-harvesting process.


Figure 3. Grain Storage Unit (GSU).

This article focuses on the post-harvest process depicted in Figures 2 and 3. The process begins with the reception of grains (CCP1), followed by the discharge into the hoppers (CCP2). The grains then undergo pre-cleaning (CCP3) to remove coarse impurities before transferred to buffer silos (CCP4) for intermediate warehousing. If needed, the grains route to dryers (CCP5) for a high-temperature treatment to eliminate moisture and ensure safe humidity levels for long-term storage. Next, the grains pass through cleaning machines (CCP6) to remove fine impurities that may affect their quality. Subsequently, the grains are stored in permanent storage silos (CCP7) until they are ready for commercialization. Once the sale is completed, the shipping process (CCP8) begins. Throughout the entire storage process, various crossing points (CCP9) contribute to the losses. The implementation of digital technologies can effectively address CCP´s, aiming to minimize losses in the overall process.

A thorough study delved into over 300 cases of loss reduction initiatives in post-harvesting [87]. The findings revealed a potential to decrease production losses from 2% to 28%, with an average reduction of approximately 7% and a standard deviation of around 11%. The study also uncovered that more than 80% of initiatives aimed at curbing losses focus on implementing storage technology interventions for farmers and 6% for traders. Consequently, it seems reasonable to anticipate that digital technologies could have an average impact of around 7% on the overall volume of produce. This estimate is comparable to reports that indicate loss reductions between 5 and 8% in production volume due to the introduction of technological management elements [88].

In a grain storage unit (GSU), the drying and storage processes are pivotal. Grain dryers are equipped with various sensors and systems to ensure efficient operation, such as pressure sensor to balances mixtures in the drying air, level sensors to prevent the equipment from operating when empty, exhaust air temperature sensor to detects early signs of fire, frequency inverter to adjusts drying speed and time, and automatic fuel sup-ply system to stabilize the drying temperature by regulating burning. To monitor grain quality, the system provides real-time measurements of grain moisture, drying air temperature, and grain mass. Real-time alert systems enhance safety and equipment efficiency. For storage, the recommendation is at least one temperature sensor per 150m³ of grain. The system transmits in real-time through a remote platform intragranular relative humidity sensors and meteorological data. The system tracks the storage evolution, grain mass temperatures, and enables the creation of rules that link the aeration system to air renewal based on climatic conditions. Safety and quality objectives may vary based on drying, cooling, conservation methods, local climate, and customer's strategy [84].

Dry matter loss or technical breakdown occurs during grain storage, leading to weight loss caused by chemical oxidation reactions that consume energy stored in organic compounds such as sugars and starches. The acceptable level of dry matter loss varies, but authors suggest values between 0.1% and 0.5% [89, 90]. In Brazil, field evidence establish-es an official technical breakage rate of 0.3% per month of storage [91].

### 3.3 Digital technology products and services for post-harvesting

The company offers a range of products and services that utilize digital technologies integrated with fixed equipment throughout the entire set of processes in the GSUs. The offers include receiving, handling, pre-cleaning, drying, post-cleaning storage and preservation, and grain shipping. Various digital field technologies assist farmers in re-al-time monitoring of grain temperature and humidity [92]. Additionally, virtual reality is utilized for training and inspection activities [93], while AI and CC are leveraged to predict the behavior of key variables in storage operations [94]. The literature provides a re-cent overview of the enabling technologies used in Agriculture 4.0 [95]. To enhance under-standing, the company categorizes its offerings into three layers of products, with the first layer being closer to the physical space and the third layer closer to the cyberspace.

The first layer encompasses sensors that collect data related to physiological conditions, such as temperature and humidity. It also involves gathering data on machine productivity and maintenance, utilizing sensors for flow, temperature, movement, bushing, and mechanical component alignment. This layer includes motors, standardized sequencing, and protection instrumentation, such as inductive and capacitive sensors, as well as protection relays. Finally, the layer incorporates specialized instrumentation, such as thermometry systems for monitoring temperature and humidity sensors for drying processes.

The second layer comprises control panels and supervisory systems that employ various automation architectures to manage the performance and efficiency of the entire process through preset management and process parameter control. In fully automated units, the panels can interact with each other (Machine-to-Machine - M2M) without human intervention, leveraging IoT technology. This capability is crucial as it supports the concept of decentralizing the automation process, enabling individual and independent control of each piece of equipment. It also allows a single control room to oversee multiple GSUs. Depending on the arrangement, the control room may or may not be located near the field. It is not uncommon for customers to control multiple GSUs from a single control room. The company exclusively sells physical equipment and add-ons from the first two layers, whether they are included in the overall engineering solution or integrated into the machinery. The equipment warranty is contingent upon the safe operating conditions ensured by the automation, control, and instrumentation systems of the first two layers.

The third layer encompasses remote digital services, typically hosted in the cloud. The company has incorporated such a service into its engineering solution since 2019. The cloud platform communicates with the second layer through gateways and internet access infrastructure. The platform features a highly adaptable interface that efficiently retrieves real-time data and information generated by the equipment's sensors. It records operation-al history, serving as a valuable resource for facilitating timely decision-making processes for both customers and equipment suppliers.

In terms of enabling technologies for the digital transformation of industrial processes, the company primarily relies on automation (AUT) and radio frequency identification (RFID) in the first layer. The second layer is predominantly supported by cyber-physical systems (CPS), the Internet of Things (IoT), and virtual reality and augmented reality (VRAR). The third layer relies mainly on big data analysis (BGA), cloud computing (CC), and simulation (SIM). Additive manufacturing (AM) plays a role in expediting the supply of spare parts and prototyping, while also facilitating the development of new technologies. It is conceivable that AM will be utilized in future machinery development, particularly due to the market's requirements for modularity and scalability. Figure 4 provides an illustration of the three layers.

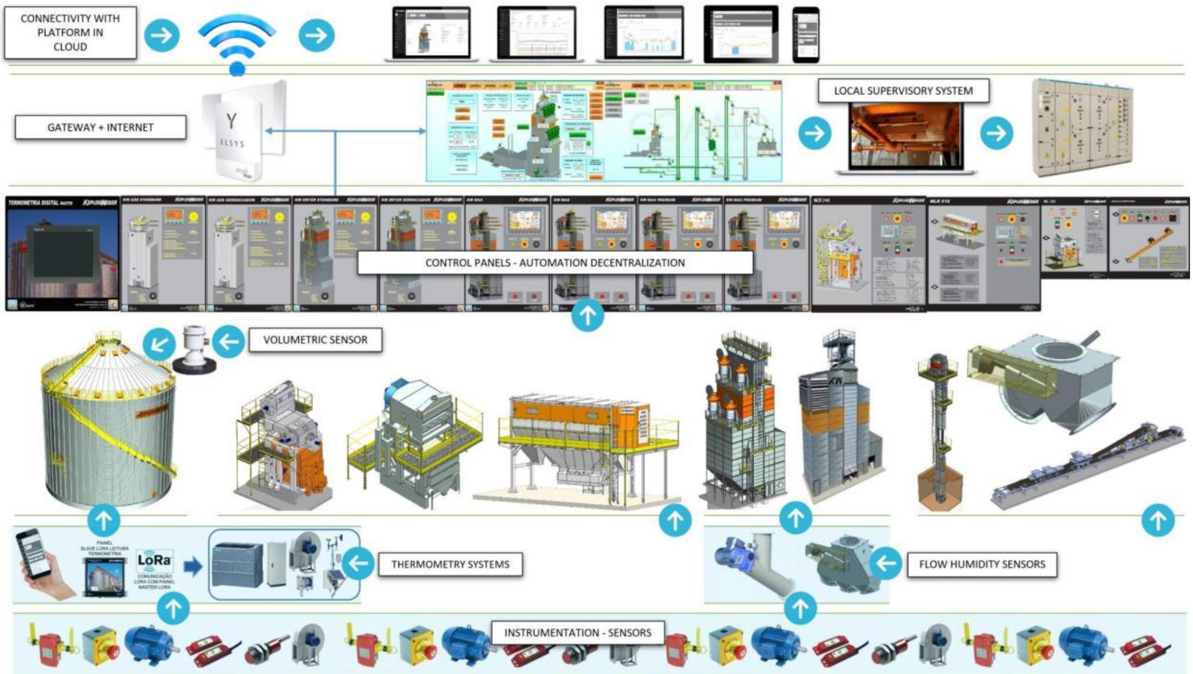


Figure 4. The three layers of digital products for post-harvesting that the company provides.

# 4 TYPES OF OPPORTUNITIES

The competitive priorities for providers of post-harvest solutions undergo changes as the market evolves in implementing and adopting GSU technology products. The company under study identifies five categories of opportunities for customers and stakeholders: financing, commercialization, operation and logistics, insurance, and traceability. The opportunities attract the interest of eight key players, each representing a potential customer for new products and services. The primary player is the agricultural producer, encompassing all types of opportunities. The other players include trading companies, agroindustry's involved in grain purchases, financial institutions, input suppliers, insurance companies, food retailers, and end consumers. Each player establishes unique competitive priorities for every viable opportunity, aligning them with their respective value perspectives. Figure 5 provides an illustration of the different opportunity types.

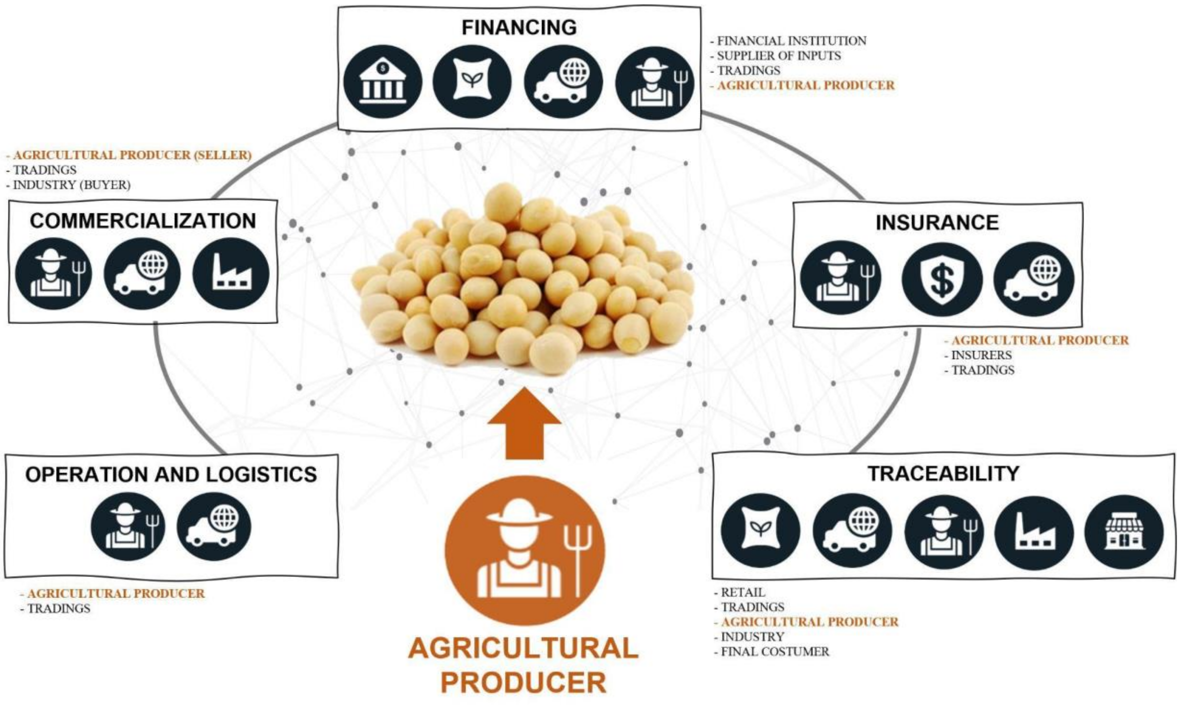


Figure 5. Opportunities for post-harvest solution providers.

Figure 6 represents a technology platform view that integrates the five types of opportunities and a sixth element, the solution provider.

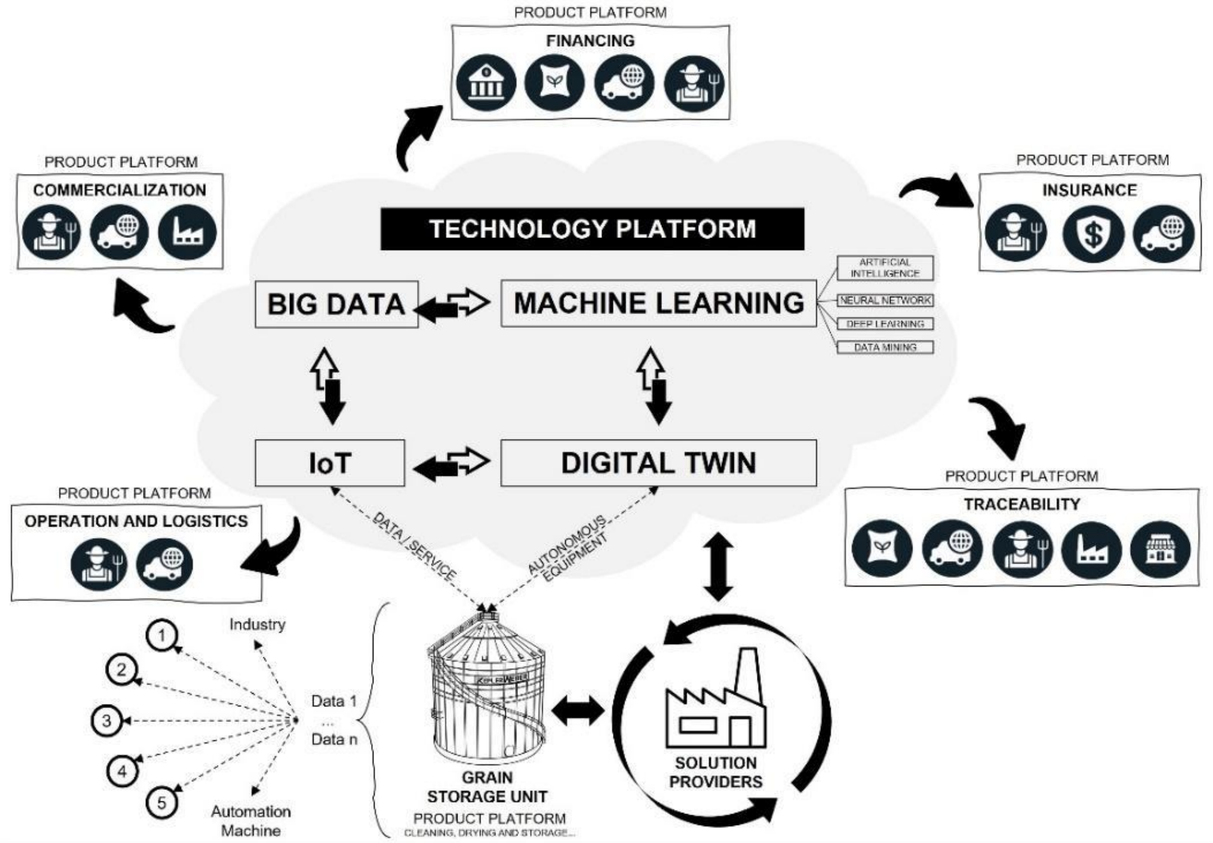


Figure 6. Technologic platform.

The key component of the system is the big data machine, which harnesses data from IoT solutions integrated into the equipment. It serves as a vital link that connects to the machine-learning device, enabling the generation of essential information for the development of new products and services linked to the platform. With the assistance of a digital twin driven by artificial intelligence and other advanced technologies, the system seamlessly integrates the automation solutions within each client's equipment. The integration not only enhances the concept of autonomous equipment but also strengthens the manufacturing industry's drive towards performance enhancement. By utilizing digital technologies to extract valuable insights and knowledge from vast amounts of data, solution providers can establish continuous connectivity with customers, even beyond the de-livery, installation, and commissioning of systems. Offering digital services positions solution providers as consultants, providing support and guidance to customers in their quest for enhanced efficiency and preservation of grain quality. Digital services open new and sustainable revenue streams, justifying investments in the development of innovative products.

The studied company addresses the specific requirements of each opportunity type, ensuring tailored solutions for their customers.

### 4.1 Exploring the Opportunities

As for financing, the main opportunity lies in digitizing the credit application process for agricultural producers, with the grain harvest serving as collateral for the loans. Financial institutions, input suppliers, and trading companies focus on minimizing default risks, while agricultural producers seek fast, affordable, and secure credit options. The platform effectively addresses the uncertainties associated with credit information and risk assessment, as well as the challenge of tracking grains covered by warranties to pre-vent fraud. In essence, the primary challenges faced by these stakeholders revolve around credit approval uncertainties, difficulties in monitoring warranted grain, and the risk of fraud. Additionally, agricultural producers face the additional challenge of convincing financial institutions to have faith in the effectiveness of their production. Historical data that showcases the producer's performance and punctuality become crucial in securing lower interest rates, gaining preferential access to financial resources, and becoming eligible for more stringent yet government-subsidized financing options.

As for commercialization, trading companies, agroindustry's, and producers share a common need for improved reliability in purchase and sale operations, along with agility and security in transactions. Trading companies and buyers prioritize reducing transaction costs and mitigating uncertainties associated with receiving goods, which involves accessing information about input and grain quality, market price quotations, minimizing storage expenses, expanding storage capacity, and establishing connections with new grain producers. Platforms effectively address these limitations by providing the necessary tools and information. On the other hand, producers aim to secure the most favorable commercial conditions in terms of price, receipt timeframe, and contract closure speed. They require access to information that reveals the correlation between grain price and quality, streamlined transaction processes, and connections to new grain buyers. Platforms effectively address these limitations by providing the necessary resources and connections to facilitate efficient and favorable trade for producers. In summary, platforms play a vital role in meeting the needs of trading companies, agroindustry's, and producers by enhancing reliability, reducing costs, mitigating uncertainties, and facilitating efficient and secure transactions.

As for operations and logistics, producers and trading companies have specific requirements. Producers are looking to expand their warehousing capacity and maintain their current equipment. They also seek solutions for maintaining grain quality through advanced quality control methods and monitoring services that improve efficiency and reduce waste along the entire grain supply chain. By integrating e-commerce solutions with IoT data from customer-installed equipment, proactive measures can anticipate preventive and predictive maintenance needs, optimizing services and parts. Additionally, the technology platform-backed e-commerce system can identify new business opportunities, such as expanding capacities in GSUs and offering equipment and technology acquisitions to both existing and potential customers. Producers face challenges, including the high costs associated with acquiring and maintaining silos, a lack of tools for grain quality control, heavy reliance on manual labor, time-consuming and costly transshipment, and transportation stages that often result in contract non-compliance, fines, and deterioration of grain quality during prolonged storage. On the other hand, trading companies encounter difficulties due to the absence of quality control tools for stored and in-transit grain, excessive reliance on manual labor in transportation, and the lack of grain monitoring during transshipment and transportation, leading to waste and losses. Such challenges ultimately have an impact on the agroindustry, food retailers, and consumers. To over-come limitations, the use of automated, integrated strategic platforms can prove beneficial. Such platforms offer comprehensive solutions that address the specific needs of producers and trading companies, streamlining operations, enhancing efficiency, and ensuring the maintenance of grain quality throughout the entire supply chain.

As for insurance, one of the main challenges is to digitize the insurance contracting process and leverage technology for intelligent risk analysis and remote monitoring of risks associated with harvest, storage, and transportation. The key stakeholders are insurance companies, trading companies, and producers. For insurance companies, it is crucial to mitigate risks by conducting more efficient and cost-effective inspections of agricultural properties to reduce fraud and cargo theft. Insurers often face difficulties due to the high-risk nature of the agricultural activity, which leads to high inspection costs, low inspection efficiency, and a prevalence of fraud and cargo theft incidents. Trading companies, on the other hand, face the challenge of enhancing security against fraud, theft, and returns. They strive to protect their interests and minimize potential financial losses resulting from these risks. Producers consider insurance as essential for mitigating uncertainties and ensuring a financial return on their crop investments. However, high insurance policy prices pose a significant difficulty for them. An integrated platform provides producers with the ability to compare prices and benefits offered by different insurers. Additionally, by presenting reliable information on historical productivity, producers can diminish the insurer's risk perception, resulting in lower-priced insurance policies for them. Overall, digitalization and the integration of platforms in the insurance sector ad-dress challenges by streamlining processes, enhancing risk analysis capabilities, reducing fraud incidents, and providing greater transparency and cost efficiency for all parties in-volved. By embracing technology and digital solutions, insurance companies, trading companies, and producers can benefit from improved efficiency and effectiveness in man-aging insurance contracts and mitigating risks associated with agricultural activities.

As for traceability, the primary challenge lies in establishing a digital platform capable of integrating information across the entire supply chain, which includes cleaning, drying, and storage processes. By incorporating comprehensive and integrated information, it becomes possible to establish standardized commercialization norms and certify the product's origin and quality for the market. The key stakeholders are producers, trading companies, buyers, and retailers. For producers, trading companies, and buyers, the certification of grain origin and journey is of utmost importance to ensure product quality. This includes aspects such as verifying the appropriate use of pesticides in harvest management. Producers face challenges related to adopting product quality standards and pressures from various stakeholders to identify and reduce pesticide usage while embracing environmentally sustainable practices. Trading companies and buyers struggle with limited monitoring capabilities throughout the transportation, storage, and processing of grains due to a multitude of suppliers and product mixes along the supply chain. Additionally, they face increasing pressure to adopt sustainable practices and ensure environ-mental safety. For retailers and consumers, the supply of nutritious, healthy, and environmentally safe food is paramount. It is equally essential to have monitoring data and assurance of food safety for the end consumers. Overcoming these challenges relies on re-liable tracking systems and accurate information regarding the origin, journey, and quality of the food products. Addressing these challenges requires the development and implementation of robust traceability systems that track and record essential data points throughout the supply chain. By leveraging digital platforms and integrating information, stakeholders can ensure transparency, reliability, and compliance with quality and safety standards. This enables consumers to make informed choices about the food while promoting sustainable practices and fostering trust throughout the supply chain.

Table 1 depicts the main implications of the study and the opportunities that digital transformation conveys for players interested in the solutions provided by the company.

Table 1. Synthesis of the implication of the study.

| | Opportunities | | | | |
|---|---|---|---|---|---|
| **Players** | **Financing** | **Commercialization** | **Operativos and Logistics** | **Traceability** | **Assurance** |
| Producers | Credit cheap and fast | Increased reliability | Increased grain quality | Origin certified | Reduced cost |
| Trading companies | Reduced default risk | Increased reliability | Increased grain quality | Origin certified | Reduced risk |
| Agroindustry | | Increased reliability | Increased grain quality | Origin certified | |
| Financial institutions | Reduced default risk | | | | |
| Suppliers | Reduced default risk | | | | |
| Insurance companies | | | | Information | Reduced risks |
| Food retailers | | | Increased food quality | Safer food | |
| Consumers | | | Increased food quality | Safer food | |

## 5 FINAL REMARKS

Digital transformation is the process an organization applies to integrate digital technologies into its business, fundamentally changing how it delivers value to customers. Digital transformation can, at the same time, increase productivity, improve the customer experience, and reduce operating costs. In post-harvest activities, particularly in GSU, digital technologies have given equipment autonomy to communicate with other machinery and collect data required by automatic platforms of strategic management.

The purpose of this article was to identify opportunities that digital transformation in post-harvest activities offers to an engineering solution provider. The research method was a simple case study. The object of study was a company based in southern Brazil that pro-vides integrated engineering digital solutions, including products and services, to grain producers. The primary findings included the differentiation of the company's products into three technological layers, the identification of five important opportunity kinds, eight players, and the potential contributions of each technology to the top players in each opportunity type. The types of opportunities are financing, commercialization, operations and logistics, traceability, and insurance. The players are grain producers, trading companies, the agroindustry that purchases grains, financial institutions, input suppliers, insurance companies, food retailers, and final consumers. The digital transformation presents a host of opportunities, many of which already implemented, across various aspects of the production chain for post-harvest services. The implications include:

(i) Digitalization of credit-taking: The adoption of digital processes and platforms for credit applications and approvals, streamlining and expediting the financing process for producers.

(ii) Digitalization of purchase operations: Implementing digital solutions to facilitate purchase transactions, improving efficiency, and reducing costs for trading companies and agroindustry’s.

(iii) Digitalization of sale operations: Utilizing digital platforms to enhance sales processes, enabling faster and more secure transactions for both producers and trading companies.

(iv) Digitalization of grain quality control: Leveraging digital technologies to monitor and control grain quality throughout the supply chain, ensuring higher standards and reducing quality-related risks for all stakeholders.

(v) Digitalization of food safety control: Implementing digital systems and technologies to enhance food safety protocols, enabling better traceability and ensuring the delivery of safe and high-quality food products to consumers.

(vi) Digitalization of grain movement information: Utilizing digital platforms to track and monitor grain movement, providing real-time information on storage, transportation, and logistics, resulting in increased transparency and efficiency in the supply chain; and

(vii) Digitalization of insurance contracting processes: Adopting digital solutions for insurance procedures, simplifying and streamlining the contracting process, reducing costs, and improving risk assessment and management for insurers, producers, and trading companies.

Integrating field equipment with management platforms is a crucial aspect of this digital transformation, enabling data collection, analysis, and decision-making. By embracing digital opportunities, the actors in the post-harvest services production chain can unlock significant value, improving efficiency, reducing risks, and enhancing overall performance. According to the Brazilian Company of Food Supply (CONAB), Brazil's grain production for the 2022/23 harvest may surpass 313 million tons [96]. The company highlights that each percentage point of error, for instance, in humidity control, may lead to a loss exceeding 3 million tons, which emphasizes the economic feasibility of employing technology to preserve the physiological and quantitative integrity of grains. By utilizing monitoring and automation systems capable of autonomous decision-making with minimal human intervention, losses diminish while augmenting the global grain supply.

The study opens room for additional research. One possibility is constructing a framework or roadmap that guides a company's digital transformation and provides post-harvest activity solutions. Another option is to survey the company's customers (there are more than a thousand rural producers around the globe already served by the studied company) to understand the digitalization stage the industry is in and, mainly, what competitive priorities rural producers aim to meet with the digitization. Finally, multiple case studies should describe the peculiarities and difficulties of customers with digitalized products and processes and the digital transformation of the implemented solutions.

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# 5 THIRD ARTICLE - FROM GRAIN TO CLOUD: IMPACTS OF DIGITAL TRANSFORMATION ON POST-HARVEST GRAIN MANAGEMENT

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## ABSTRACT

This article examines the impacts of digital transformation on the outcomes of a company in the post-harvest sector, identifying strategies to overcome the challenges associated with this transition. It employs two complementary methodological approaches: a case study of a post-harvest process solutions provider and an analysis of best practices from a German research institute. The results highlight the effect of these innovations on reducing energy consumption, improving grain quality control, ensuring process efficiency, and enhancing food safety. In the drying process, the identified innovations demonstrate potential operational gains estimated at USD 700 million annually in Brazil. Additionally, the research shows the ability of these innovations to generate both quantitative and qualitative economic value, benefiting not only the post-harvest sector but the entire agricultural supply chain. The primary implication of the research underscores the importance of creating an internal digital framework, which is crucial for the successful implementation of a digital transformation strategy. Furthermore, the acquisition of a technology player minimizes dependence on external suppliers, ensuring greater control over innovations and costs. Emerging technologies identified in Germany are relevant for overcoming the challenges of digital transformation and guiding corporate strategies. This work provides valuable insights for companies and researchers seeking to explore the opportunities of digitalization in the post-harvest grain sector, emphasizing economic and efficiency gains in drying and storage units.


Keywords: agriculture; grain; post-harvest; digital transformation; impacts.

## 1 INTRODUCTION

With the rapid advancement of the digital economy, the digital transformation of enterprises has gained significant attention across various sectors. It has emerged as a crucial strategy for traditional companies, fundamentally reshaping operations and business models to maintain competitiveness (Ponsignon et al., 2019). This transformation has led to substantial changes in organizational activities, processes, and capabilities (Fatorachian et al., 2019; Ardito et al., 2019). Digital transformation is characterized by the combined effects of diverse innovations and technologies, which introduce new actors, structures, practices, values, arrangements, and beliefs into competitive landscapes, thereby altering, displacing, replacing, or complementing ecosystems within private, public, small, medium, and large organizations, as well as industries (Westerman et al., 2014). It involves three key elements: (i) the reorganization and redefinition of company boundaries; (ii) the broadening of products and services to reach a wider consumer base, accompanied by a reduction in property rights; and (iii) the reconfiguration of organizational and product identities (Parmentier & Mangematin, 2014).

An increasing number of companies have adopted digital transformation strategies to enhance value creation and appropriation. As a result, these companies must reassess and revise the current architecture of their value creation and appropriation models to sustain a competitive advantage. Moreover, a critical requirement for companies undergoing digital transformation is the renewal of their business models to align with their overarching business strategy (Iansiti et al., 2019; Pigni et al., 2016; Warner et al., 2019).

The agri-food industry, which addresses global food needs, generates substantial employment, contributes significantly to economic growth, and has considerable environmental impacts, faces an urgent need to develop economically, socially, and environmentally sustainable long-term solutions (Jambrak et al., 2021). Historically, the food industry has evolved through phases focused on food integrity and safety (until 1950), flavor enhancement (1950-1980), and health (1980-2000), with the current phase emphasizing the promotion of "societal health" (Silva et al., 2018; Augusto, 2020). Digital transformation encompasses a suite of advanced technologies that can significantly impact this sector. These technologies can be applied across various business functions, influencing products, processes, factories, and supply chains (Hasnan & Yusoff, 2018; Manavalan & Jayakrishna, 2019). For instance, the integration of the Internet of Things (IoT), automation, and robotics into production plants enhances operational efficiency (Bortoluzzi et al., 2020), while big data and analytics support strategic decision-making across multiple organizational levels, from operations to marketing (Ferraris et al., 2019; Rialti et al., 2019). In post-harvest grain management, digital transformation offers practical solutions to challenges related to quality standards, energy consumption, and cost reduction (Hasnan & Yusoff, 2018), while also mitigating the uncertainty and risks inherent in agri-food supply chains (Lezoche et al., 2020).

The digitization of post-harvest processes improves the efficiency of natural resource utilization, reduces waste, and enhances sustainability (Schmidt et al., 2024). However, the application of enabling technologies for digital transformation varies across companies and operational contexts, and the agri-food sector has been less explored compared to manufacturing (Muller et al., 2018; Manavalan & Jayakrishna, 2019). Research on digital transformation technologies in the agri-food sector primarily consists of literature reviews and theoretical studies (e.g., Rana et al., 2021), with a focus on technological applications in agriculture (e.g., Trivelli et al., 2019).

Empirical research examining the effects of digital transformation on post-harvest activities, including influencing factors and the outcomes of adopting such technologies, remains sparse. This study aims to fill this gap by employing two complementary methodological approaches: a case study of a Brazilian company specializing in engineering solutions for post-harvest grain activities and an analysis of best practices from a German research institute. The primary objective is to assess the impact of digital transformation on the performance of the focal company. Additionally, the study aims to evaluate the strategies employed to achieve digital transformation, analyze its effects on the competitive advantages of the company and its clients, and explore, through insights from the German research institute, the new digital technologies under investigation globally. This exploration seeks to determine how these technologies can be applied to post-harvest grain management and their potential to influence the digital strategy of the company under study.

The article presents empirical evidence on digital transformation in post-harvest grain management and is structured as follows: Section 2 reviews the literature on digital transformation in companies, highlighting the challenges and strategies involved; Section 3 outlines the methodological procedures adopted for the case study; Section 4 presents the case study and an analysis of best practices from a German research institute; Section 5 discusses the results, offering a theoretical analysis of the company’s digital transformation strategy and its observed outcomes; Section 6 provides concluding remarks and final considerations.

# 2 LITERATURE REVIEW

## 2.1 Strategy for Digital Transformation

The adoption of digital transformation strategies presents numerous challenges (Cennamo et al., 2015; Davenport et al., 2018; Kane et al., 2015). Recent estimates indicate that 66% to 84% of digital transformation projects fail (Libert et al., 2016), a significant proportion considering the substantial monetary and non-monetary costs involved. A central challenge lies in ensuring alignment between the formulation and implementation of the strategy for digital transformation (Beer et al., 2000; Crittenden et al., 2008; Chanias et al., 2019). Although interdependent, strategy formulation and implementation are distinct processes. Digital strategy formulation involves defining a policy to create and capture value through the effective use of digital technologies, with the aim of achieving long-term objectives. This process includes consideration of external environmental factors, technological potential, the competitive landscape, and market evolution. Thus, strategy formulation must identify the elements of the company's business model that require modification in alignment with the new strategy and the scope of digital transformation (Alessia et al., 2020).

Digital strategy implementation involves translating the formulated strategy into a concrete plan and set of actions (Noble et al., 1999; Gimbert et al., 2010; Rothaermel et al., 2017). Effective implementation is essential to ensure consistency between company actions and the objectives outlined during strategy formulation (Rothaermel, 2017). However, existing literature often assumes that once a strategy is defined, implementation will naturally follow (Feurer et al., 1995; Dayan et al., 2017). In practice, this assumption does not always hold true, and senior executives cannot derive benefits from digital transformation strategies if they fail to implement them effectively (Beer et al., 2000; Crittenden et al., 2008). The success of strategy implementation is more critical to avoiding failure than the quality of strategy formulation (Lee et al., 2016; Greer et al., 2017). While precise implementation allows for adaptation to changing conditions (Chanias et al., 2019) and can rectify imprecise formulation (Lee et al., 2016), even the most well-formulated strategy holds little value without proper execution (Greer et al., 2017).

The rapid advancement of digital technologies and the extensive data generated by devices and applications are compelling companies to fundamentally transform their business architecture to enhance value creation and capture.

## 3 RESEARCH METHOD

Gil (2010) defines exploratory research as aimed at increasing familiarity with a research problem, clarifying it, or developing hypotheses. Nielsen et al. (2018) add that exploratory research focuses on gaining a better understanding or detailing aspects of a relatively unknown phenomenon. This study is exploratory in nature, as the digital transformation process in post-harvest solution providers is still not well understood.

This research employed the case study method, using multiple techniques to gather comprehensive data. The primary method was non-participant direct observation, where the researcher monitored key activities in real-time without influencing the outcomes. The choice of the case study method is justified by the aim to identify "how" digital transformation is impacting the company and the chosen sector. Digital transformation is an ongoing process, making it difficult to separate the phenomenon from the current context of the companies. Subsequent sections will provide detailed information on the specifics of this method, including the selection process and execution procedures.

In addition to direct observation, the study incorporated semi-structured interviews with key employees and clients of the company under investigation. These interviews provided valuable insights into the actions, challenges, and impacts associated with digital transformation in the context of post-harvest grain operations. To identify new digital technologies relevant to the company's digital strategy, an empirical investigation of international best practices was conducted, involving non-participant observation at a German research institute and semi-structured interviews with researchers specializing in new technologies. This combination of techniques facilitated a comprehensive understanding of the company's processes, customer needs, and organizational strategies related to digitalization.

A bibliometric analysis was conducted to establish the current state of research on digital technologies in grain post-harvest processes. This analysis provided a broader context and theoretical foundation, identifying knowledge gaps and guiding the case study.

The case study approach was selected for its ability to explore phenomena within their natural context, offering a holistic analysis of the interactions between various elements involved in the digital transformation of grain post-harvest operations. This qualitative approach was supplemented by quantitative analyses, such as evaluating financial performance indicators before and after the implementation of digital technologies. The study aimed to capture the complexity and dynamics of the digital transformation process, providing a comprehensive view of the impacts and challenges faced by organizations in the agricultural sector.

The focus of the study was a Brazilian company specializing in engineering solutions for post-harvest activities. Founded in 1925, the company is a leader in Latin America, holding a 40% market share in Brazil. It offers solutions for grain processing, handling, and preservation, covering the entire value chain from farm origination to logistics terminals at ports. The company also provides project implementation management and services for modernization and upgrading of processing units. It has been publicly traded since 1980 and operates in over 50 countries across five continents.

The study included the following stages:

(i) Review of documents issued by the engineering solutions company.

(ii) Guided tours of the company's facilities and two client facilities, accompanied by company professionals.

(iii) Interviews with the company's portfolio managers and specialists.

(iv) Interviews with two final clients of the company.

(v) A final meeting where the researcher presented findings to managers and clients for verification and adjustment, ensuring reliability.

The impact of Industry 4.0, launched by the German government in 2012, has significantly influenced the company under study. Therefore, empirical research on international best practices involved collaboration with the Bremer Institut für Produktion und Logistik GmbH (BIBA) in Bremen, Germany. Founded in 1981, BIBA is a leading research institution affiliated with the University of Bremen, focusing on application-oriented and industrial contract research in production and logistics.

The empirical research at BIBA involved:

(i) Review of projects, documents, and new technologies provided by the institute.

(ii) Guided tours of BIBA’s facilities, with discussions led by professors and researchers involved in relevant projects.

Table 1 highlights the diversity and qualifications of the interviewees, all of whom have relevant experience in grain post-harvest processes and/or in research that develops new technologies. The methodology of unstructured interviews used for data collection allowed for a more flexible and interactive approach, enabling the exploration of specific perceptions and experiences of the participants. This contributed to the collection of deep insights into the implementation of emerging technologies in the agricultural sector.

| Research Object | Activity | Academic Background | Degree |
|---|---|---|---|
| Company | Director of Digital Services | Administration | Master's |
| | R&D Coordinator | Chemical Engineering | Bachelor's |
| | Product Engineer | Agricultural Engineering | Bachelor's |
| | Product Owner | Agricultural Engineering | Doctorate |
| | Automation Analyst | Electrical Engineering | Bachelor's |
| | Electrical Designer | Electrical Engineering | Bachelor's |
| | Technology Product Analyst | Computer Science | Bachelor's |
| | Storage Unit Manager (Customer) | Agricultural Engineering | Bachelor's |
| | Storage Unit Manager (Customer) | Agricultural Engineering | Master's |
| Research Institute | Scientific Director | Electrical Engineering | Doctorate |
| | Research Coordinator | Engineering Economics | Bachelor's |
| | Researcher | Aerospace Engineering | Master's |
| | Researcher | Industrial Engineering | Bachelor's |
| | Researcher | Mechanical Engineering | Bachelor's |

Table 1: Profile of Interviewees.

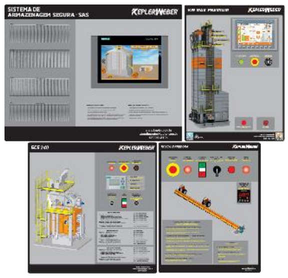
The research employed both qualitative and quantitative analyses to assess the impacts and qualitative aspects of technologies. It focused on describing the strategy adopted by the company for digital transformation, identifying its impacts, and evaluating technological trends for future initiatives. Given the case study approach, the findings are not intended to provide external validity but are specific to the scope of the research. Future studies should consider broader sector-wide analyses to enhance external validity. The final meeting with participants, where they reviewed and revised the findings, strengthened the internal validity and reliability of the study. As an exploratory and qualitative study, it provides initial insights into the problem, offering a descriptive analysis that may prompt further research.

# 4 RESULTS

## 4.1 Digital Transformation in Products

The dynamics of digital transformation have varied across different sectors of agriculture. Innovations in equipment and inputs involved in grain production up to harvesting have led to a notable increase in yield per hectare. Batista (2020) attributes these advancements to several key actions. Firstly, genetic improvements in seeds have enhanced their adaptation to diverse geoclimatic conditions and resistance to increasingly effective agricultural chemicals. The development of pesticides over successive generations has addressed rising pest resistance. Secondly, digital transformation has introduced innovations in field operations, enabling precision agriculture through improved equipment connectivity. Advances in large-scale machinery used for planting, protection, and harvesting have increased precision, minimized losses, and optimized productivity per unit area. Enhanced techniques in planting, fertilization, and irrigation have further increased land productivity. Precision agriculture enables producers to segment fields and tailor operations to specific stages and needs (Batista, 2020).

In contrast, equipment for post-harvest grain processing has evolved along a trajectory established over previous decades. According to Batista (2020), innovations have focused on maintaining grain quality post-harvest and increasing processing capacity. Silos, dryers, cleaning machines, and grain conveyors have expanded to accommodate the growing volume of grain. Inspired by the digital transformation in grain production and responding to new market demands, the company under study, a provider of engineering solutions for post-harvest, has embarked on advancing its digital transformation within this segment and exploring opportunities offered by digital technologies. The company's objectives for digital transformation include developing long-term autonomous equipment and storage units, reducing post-harvest losses, and creating a new revenue model based on data (Schmidt et al., 2023). The company initiated a digital transformation project within its product development engineering research (P&D), implementing gradual tactical changes over the past decade. Each action was reviewed for effectiveness before planning subsequent moves. Table 2 describes four phases identified from interviews and their connections over time, and presents a fifth new phase:

| | | |
|---|---|---|
| **(i) Technological Standard** | The initial major step in digital transformation involved defining a technological platform for monitoring and automating storage units. Prior innovations had been implemented without a unified technological platform, relying on various local suppliers and differing technological solutions. Despite the absence of a clear corporate strategy for digital transformation, this step was critical in establishing a technological standard across equipment. By adopting Industry 4.0 principles, the company centralized automation concepts previously used in storage units, standardizing the automation architecture with embedded industrial control PLCs. This transition from low-cost, low-robustness solutions to higher-quality technology improved local automation networks, facilitated information exchange using standard protocols, and enabled centralized control via supervisory systems. These advancements led to improved post-harvest process quality, enhanced equipment efficiency, increased operational safety, reduced labor, and minimized storage losses. |  |
| **(ii) Connectivity** | Following the stabilization of the technology platform, the second phase focused on enhancing connectivity. With standardized technology, data collection and storage became routine across equipment. Embedded automation solutions began serving dual functions: real-time operational adjustments and synchronization of equipment operation information with a cloud-based data platform via an internet-connected gateway. This development allowed end customers to remotely monitor machine operations, access alerts, and review operation histories from various internet-connected devices. For the first time, the company gained real-time access to equipment parameters and operational conditions post-technical delivery and startup. |  |
| **(iii) Digital New Structure** | The advancement in digital technologies and the growing importance of data prompted the establishment of a more robust internal structure dedicated to managing digital projects. A new Digital division was created within the organization, linked to the strategic services pillar. This division was tasked with overseeing digital technology innovations for products and services, business rules, and the development of automation and connectivity solutions. |   |
| **(iv) Inorganic Growth** | To expedite the digitalization of post-harvest operations, the company acquired a prominent market player with expertise in technology products for post-harvest and a broad client portfolio. This acquisition strengthened the internal Digital division and facilitated the development of major technological solutions for post-harvest grain processing. Following the acquisition, the company began offering remote monitoring services, active consultancy, and generating recurring revenue through subscription-based services. Additionally, the company gained control over the manufacturing of key technology products included in its portfolio. | PROCER AGROINTELIGÊNCIA DE PÓS-COLHEITA |

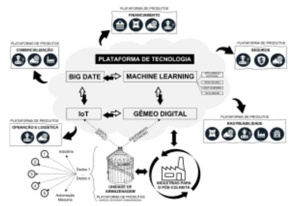
| | | |
|---|---|---|
| (v) Data Management | The substantial increase in data volume from field operations, coupled with opportunities to convert this data into organizational and client value, has catalyzed the need for the next strategic initiative. The internal Digital division, integrated into the inorganic growth model, which includes new acquisitions, highlights the necessity for a more robust structure dedicated to data research and analysis. Data research projects have been initiated to identify patterns, trends, and opportunities from the equipment data, employing techniques, mathematical models, and advanced methods to convert raw data into actionable insights that benefit both the company and its clients. Establishing an integrated environment through a centralized data repository (data lake) and a system for converting this large volume of data into usable information (data warehouse) will be essential. This will involve applying mathematical models and advanced artificial intelligence methods, such as generative artificial neural networks. |  |

Table 2: Strategic Movement.

Figure 1 illustrates the sequence of these movements and the pace at which the company implemented digital transformation actions.

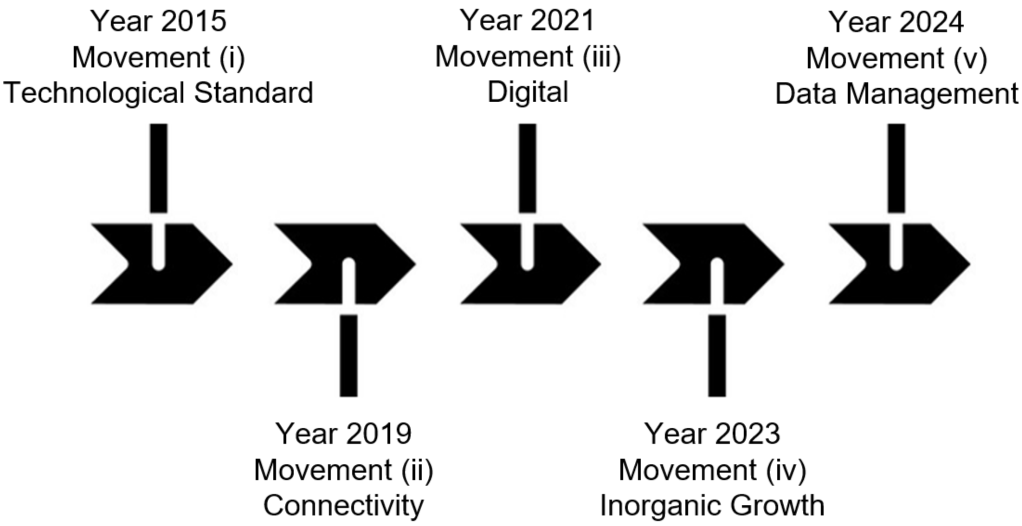



Figure 1: Strategic Movement (developed by the author).

As each new initiative is implemented within the organization, the absence of a long-term corporate strategy for digital transformation becomes increasingly apparent. Various digitization projects have emerged from efforts to advance the product portfolio. Notable projects include initiating sales on online e-commerce platforms, overcoming traditional business relationship barriers, and implementing Building Information Modeling (BIM) for execution projects (civil, mechanical assembly, electrical, and automation) in grain storage units. BIM offers an integrated and collaborative approach, using three-dimensional models to digitally represent all information related to the lifecycle of new storage units.

In the context of grain storage units, BIM allows for the creation of detailed models that include the structure's geometry, material information, construction processes, mechanical and electrical systems, as well as logistical and management data. This approach enhances project visualization, fostering effective communication among project participants, including designers, engineers, managers, and operators. By integrating precise and updated data into a collaborative digital environment, BIM aids in optimizing planning, execution, and maintenance of grain storage units, leading to improved operational efficiency, cost reduction, and greater sustainability throughout the infrastructure's lifecycle.

The combination of these projects, along with the acquisition of the technology company, underscores the necessity of establishing a clear corporate strategy for digital transformation. Developing a strategy that integrates digital transformation into the organization has become a priority. This strategy must be formulated by the highest levels of the organization to ensure alignment and coordination of subsequent tactical moves across all levels of the corporate structure.

## 4.2 Qualitative Impacts

The impacts of digital transformation refer to the effects experienced by business organizations as a result of this transformation process. Morakanyane et al. (2017) classify these impacts into two categories: customer-focused and organization-focused. The customer-focused category pertains to effects that impact customers, while the organization-focused category affects the organization itself. These impacts can manifest as either positive or negative for both customers and the organization. Morakanyane et al. (2017) note that various studies describe the effects of digital transformation using different terminologies; however, the ultimate goal for organizations leveraging digital transformation is value creation for both the organization and its customers.

The pursuit of differentiation within the sector is facilitated by the implementation of digital transformation. Schmidt et al. (2023) observe that competitive priorities for post-harvest solution providers shift as the market evolves with the adoption of technology products in grain storage facilities. Table 3 describe seven key impacts were identified in the organization under study, resulting from strategic movements towards digital transformation in post-harvest processes.

Impacts 1, 2, and 3 focus on customer value, while impacts 4, 5, 6, and 7 concern organizational value.

| | |
|---|---|
| (i) Grain Quality | Grain, being a living organism, requires proper conditions to maintain its nutritional properties. It generates CO2 and necessitates controlled storage conditions such as temperature, humidity, and pest management. Research indicates that inter-granular relative humidity should not exceed 65%, as higher levels foster fungal growth. For instance, aflatoxin aspergillus flavus thrives at temperatures of 30°C and humidity of 70%, conditions common in tropical countries like Brazil. Digital technology products enable monitoring and control of optimal storage conditions, directly affecting global food safety. |
| (ii) Customer Experience | The adoption of digital technologies has improved the customer experience by enhancing equipment usability and interaction with the organization. Customers can now access real-time operational data, optimize machine usage, and achieve better performance in storage units. This includes improved interfaces on machine HMIs, cloud-based remote access, real-time information, personalized service, and more efficient technical support. |
| (iii) Product Innovation | Digital transformation has facilitated the integration of new technologies into the company's product offerings. Innovations include new sensors, automation solutions for operational safety, grain quality, and energy efficiency, as well as IoT devices and data analytics. Grain dryers now feature embedded digital monitoring technology as a standard. |
| (iv) Brand Reputation | Enhanced equipment efficiency, driven by advancements in data collection and automation systems, has led to faster grain receiving cycles, reduced labor costs, increased capacity to meet post-harvest demands, and improved grain quality through efficient cleaning, drying, and storage. These improvements bolster the organization’s commitment to delivering high-quality equipment, thereby enhancing its brand reputation. |
| (v) Agility and Flexibility | Digital transformation has increased organizational agility and flexibility, allowing for rapid adaptation to changes in the business environment. The modularization of the technological platform, incorporating optional functionalities, improves customer satisfaction and market competitiveness. Utilizing a market-based technological platform rather than a proprietary one has facilitated better inventory management, reduced lead times, and improved responsiveness to market demands. |
| (vi) New Business Model | Digital transformation has enabled new business models, including subscription-based services, remote monitoring, predictive maintenance, and additional value-added services. This diversification of revenue streams, along with data collection and analysis, supports strategic decision-making, demand forecasting, market trend identification, and internal process optimization. |
| (vii) Organizational Culture | Digitalization necessitates a cultural shift towards embracing innovation and adaptability. Developing new products requires a focus on how digital technology can enhance competitiveness, efficiency, and security from the outset. Integrating digital solutions effectively into product development processes is crucial for achieving desired outcomes. |

Table 3: Qualitative Impacts.

Additionally, other companies in the engineering solutions sector for post-harvest have followed the market leader’s lead, initiating their own digital transformation efforts. This competitive response has spurred a broader industry movement towards post-harvest digitalization. Creating value remains the central goal of digital transformation, emphasizing the need to align digital strategies with business objectives and market demands. This approach highlights the importance of strategically implementing digital technologies to generate beneficial outcomes for all stakeholders.

## 4.3 Quantitative Impacts: Financial for the Company

The EBITDA margin of an organization represents the operating profit before financial expenses, taxes, depreciation, and amortization, expressed as a percentage of net revenue. Figure 2 illustrates the organization's net revenue alongside the historical EBITDA margin percentage over the past 14 years. A regression analysis was conducted on the EBITDA margin percentage for the period from 2010 to 2014, which precedes the organization's initial move towards digital transformation in its product portfolio. The trend line (a), defined by the equation $y = 0.0106x + 0.1176$, indicates an annual increase in the EBITDA margin of 1.06 percentage points during this period. This trend experienced a disruption shortly after the organization implemented the new technological standard in its products.

Following the initial move, the trend line (b), described by the equation $y = 0.046x - 0.3537$, reveals an annual increase in the EBITDA margin of 4.55 percentage points, commencing in 2016, the year after the initial move. After the significant milestone of the first move in 2015, the company's EBITDA margin growth accelerated, increasing by 429%. This increase can be attributed to several factors, including cost reduction, market expansion, price increases, improved supplier management, product/service innovations, financial management efficiency, and the strategic repositioning of the organization to differentiate its brand through premium product and service offerings. The adoption of advanced digital technologies from 2015 onwards reinforced this positioning and contributed directly to improved financial outcomes in subsequent years.

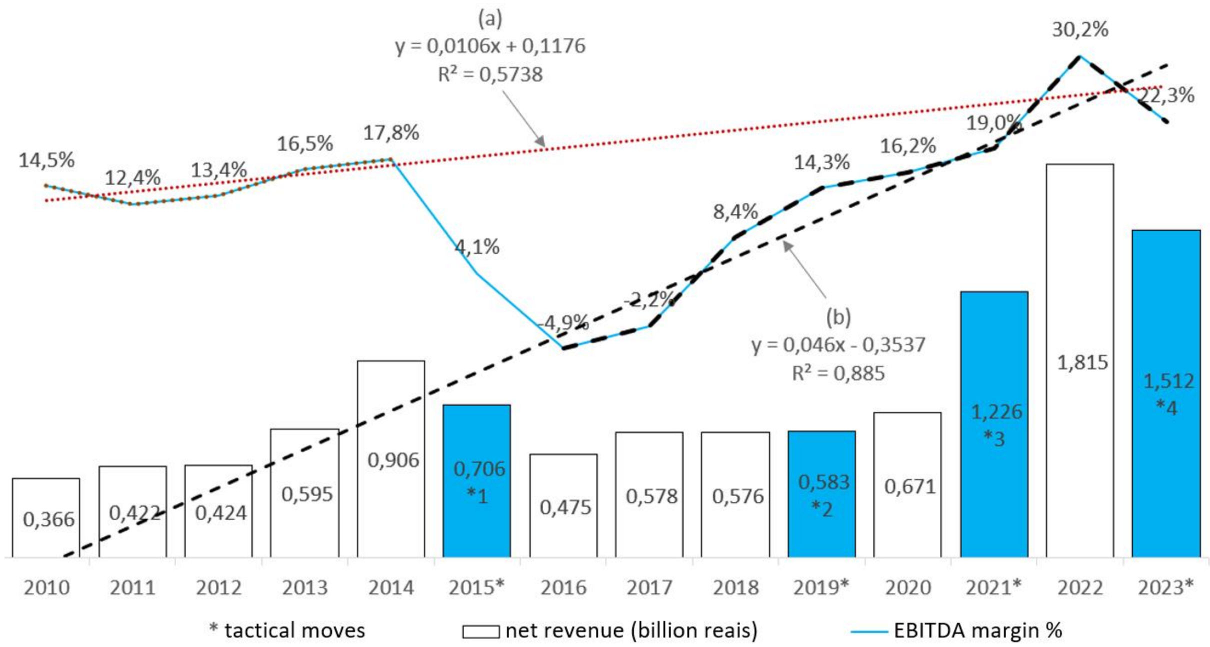



Figure 2: Net Revenue and EBITDA Margin of the studied company.

## 4.4 Quantitative Impacts: Post-Harvest

An efficiency analysis was carried out in the grain storage processes in silos provided by the company. These silos are equipped with digital technology linked to a cloud platform responsible for monitoring and providing consultancy services. The analysis employed the Data Envelopment Analysis (DEA) mathematical model to evaluate the overall efficiency of these digital-equipped silos. The assessment focused on three aspects: quantitative efficiency, indicated by technical losses due to moisture during storage; qualitative efficiency, measured by the reduction in grain mass temperature during storage; and energy efficiency, represented by the ratio of installed power for aeration systems, hours of aeration performed, and the volume of stored grain.

The research method was an analytical case study that analyzed 6,000 storage silos distributed across Brazilian territory, representing 12% of all static capacity available in Brazil. The results of this analysis showed an average grain storage efficiency in Brazil of 84%, with 84% of the silos considered as reference silos in the benchmark having digital technology for automatic control of their aeration systems. The analysis also identified a 91% reduction in technical losses due to moisture in silos equipped with digital technology, compared to the national average reported by CONAB (National Supply Company). Additionally, automatic aeration systems demonstrated a 5% improvement in quantitative efficiency over systems that only monitored conditions digitally.

The study provided strong evidence of a positive correlation between storage efficiency and the use of digital technologies in equipment, as well as correlations with storage duration and ambient temperature conditions at the installation site (see Figure 3).

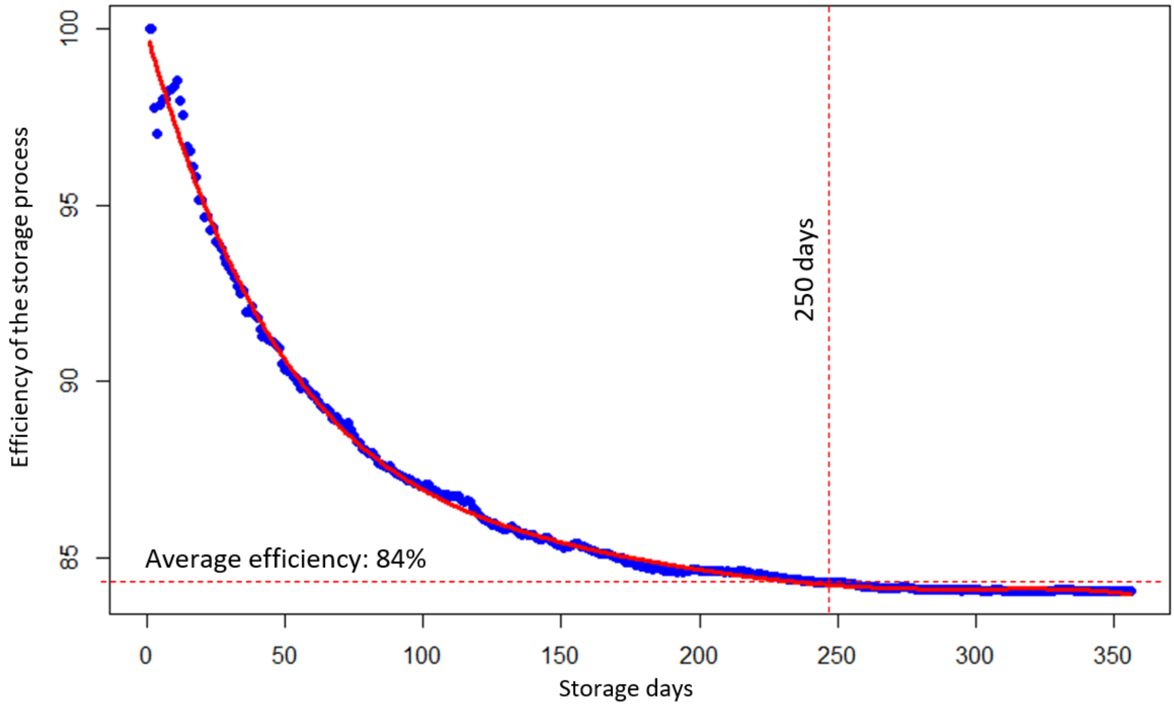



Figure 3: Storage Efficiency vs. Storage Days.

Digital technologies have notably enhanced the grain drying process. For safe storage, soybeans must be maintained at a moisture content of 13%. Grain dryers are critical in removing excess moisture to achieve this. Incorporating advanced digital instrumentation into the drying process helps to reduce operational errors. A 1% error in drying can lead to substantial economic losses. For instance, Figure 4 illustrates a silo with a storage capacity of 100,000 sacks of soybeans, valued at approximately US$ 2.8 million at a reference price of US$ 28.00 per sack. A 1% error in drying could result in a loss of US$ 28,000 per silo.

In Brazil, which is projected to produce 153.8 million tons of soybeans in the 2023 harvest, a 1% drying error would translate into a potential loss of USD 700 million. Thus, the integration of digital technology in monitoring and controlling drying moisture plays a crucial role in minimizing post-harvest losses.

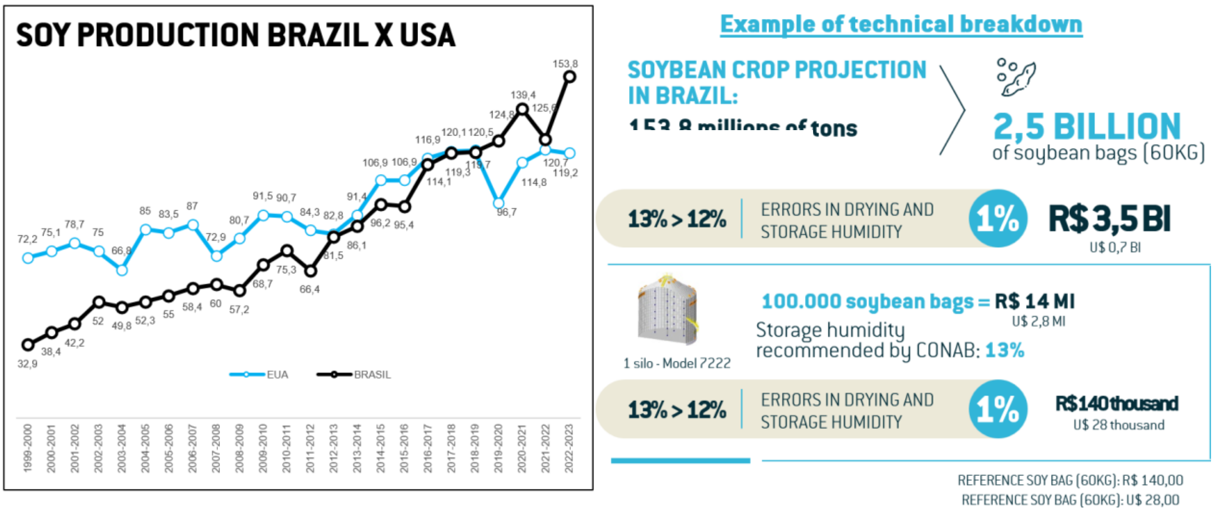



Figure 4: Soybean Production vs. Losses in the Drying Process.

Investments in technology products integrated into the equipment purchased by clients represent, on average, 3.2% of the total expenditure for acquiring storage unit equipment. Although this percentage is relatively low for new installations, clients report a clear recognition of the value of these technologies over years of use. They generally experience amortization of this investment within the initial harvests.

### 4.5 Context of Digitalization in the Company

The implementation of a digital transformation strategy involves several barriers and risks. One significant challenge is the adaptation of existing mechanical designs for automation. Current equipment may not be initially designed for automated control, necessitating substantial investments in research and development, as well as modifications to existing products. R&D teams must carefully evaluate and redesign equipment and flow valves to enable automation and achieve precision levels not previously required. Many automation projects face delays due to the need for such mechanical adjustments, prioritizing these updates over other development activities.

Another challenge is the cost of integrating digital technology, which can affect market competitiveness. Investing in technological innovations to stay relevant can lead to increased product prices, potentially impacting customer acceptance.

Although customers quickly recognize the value of digital technologies when incorporated into new installations, their perception may differ when these technologies are purchased separately or for upgrades to existing storage units.

Rapid advancements in product technology can render recently introduced solutions obsolete, necessitating frequent updates and ongoing investment to maintain competitiveness. Ensuring effective integration across diverse technologies poses difficulties, particularly due to the lack of standardized protocols that facilitate interoperability. Developing solutions compatible with various existing technologies is essential.

The growing emphasis on sustainable practices and social responsibility also impacts digital solutions for grain post-harvest. These solutions must address operational efficiency while considering environmental, social, and safety impacts to meet increasing consumer expectations and regulatory requirements.

Resistance to change within the organization constitutes another barrier. Management and employees may struggle to adapt to new roles and technologies, underscoring the need for effective training and strategic alignment at all organizational levels.

The digital transformation has led to the establishment of a new internal unit dedicated to Digital, positioned between the product development engineering (R&D) and information technology (IT) departments. IT focuses on enhancing productivity, ensuring information security, and supporting company operations, while R&D is dedicated to new product development and mechanical performance. The new Digital unit, comprising experts in automation systems, electrical engineering, and software development, plays a crucial role in bridging the gap between R&D and IT. This unit facilitates the integration of technological advancements into new digital products for post-harvest applications.

Data collection from post-harvest equipment is essential for modernization in agriculture, enhancing operational efficiency and decision-making. However, this also introduces significant security and privacy challenges, particularly with IoT solutions. Internet-connected equipment is vulnerable to cyberattacks, which can result in operational damage, data theft, or production interruptions. Implementing robust security measures, such as firewalls, data encryption, and user authentication, is vital to safeguard against cyber threats.

Data collected, including grain status, storage conditions, and meteorological information, is strategically important. Protecting this data is crucial to maintain competitiveness and customer trust. Compliance with data privacy regulations, such as LGPD in Brazil and GDPR in the European Union, requires careful management of data collection and storage practices to ensure user consent and security.

Workforce qualification extends beyond the Digital unit to encompass manufacturing, sales, assembly, technical delivery, and after-sales support. The company must invest in training or recruit talent to meet the demand for specialized technical knowledge. Additionally, supporting the workforce at the customer end to maintain automation systems is crucial. Insufficient skills in this area can lead to operational issues, affecting customer satisfaction and retention. Effective training strategies are essential to manage the steep learning curves associated with new technologies.

The analysis identified seven key areas for implementing digital technologies in the company, (i) Sustainable product portfolio, (ii) Digital infrastructure, (iii) Cultural and human resource barriers, (iv) Technology cost, (v) Workforce qualification, (vi) Technological and integration challenges and (vii) Strategy review.

### 4.6 Context of digitalization in German agriculture

Digitization is increasingly prevalent across various sectors, including agriculture. In Germany, the digitalization of agriculture is recognized as a significant development within the agri-food sector (Rohleder & Krüsken, 2016). The objective of implementing digital technologies in agriculture is to enhance productivity and efficiency, thereby contributing to sustainable development (El Bilali & Allahyari, 2018). A range of digital technologies, including positioning systems, sensors, and farm management information systems (FMIS), is being adopted to modernize and optimize agricultural operations (Mintert et al., 2016; Weltzien & Gebbers, 2016).

Despite the considerable potential of digitalization, the current state of this transformation in German agricultural enterprises reveals several challenges. The full adoption of digital systems is impeded by inadequate infrastructure and insufficient knowledge (Möller & Sonnen, 2016). This analysis will explore the opportunities, risks, and obstacles associated with the implementation of digital technologies in German agriculture, with the aim of providing recommendations for their adoption.

Munz et al. (2019) conducted a study to assess perceptions and realities of digitalization in German agriculture using an online quantitative questionnaire. This survey targeted agricultural companies and cooperatives throughout Germany, conducted in two phases from January to February 2018, with a sample of 4,731 respondents and a response rate of 8.4%. Exploratory factor analysis was employed to identify key factors related to opportunities, risks, and obstacles to digitalization in German agriculture.

Factor analysis identified six main challenges for the implementation of digital technologies in German agriculture:

(i) Economic and Ecological Advantages (Factor 1): This factor included six variables related to perceived benefits of digitalization, such as cost savings, resource efficiency, early detection of animal diseases, and improved animal welfare. Larger farms and those with higher educational levels perceived these benefits more significantly. The positive correlation between the importance attributed to digital systems and these economic and environmental benefits highlighted the substantial advantages of digitalization in agricultural operations.

(ii) Improved Intercompany Coordination (Factor 2): This factor emphasized the importance of coordination among agricultural companies for effective use of digital systems. Simplified data management through IT systems was seen as crucial for enhancing transparency and inter-company coordination. The positive correlation between the importance of data management and IT systems underscored their role in facilitating coordination.

(iii) Socioeconomic Risks (Factor 3): This factor reflected concerns about socioeconomic risks associated with digitalization, such as increased controls, data protection issues, and excessive complexity. These risks represent significant obstacles to the widespread adoption of digital technologies and require careful mitigation strategies.

(iv) Financial Risk (Factor 4): Financial concerns related to digitalization, including uncertainty about return on investment and investment risk, were highlighted by farmers. The negative correlation between the importance of digitization and this factor indicated that profitability is a crucial consideration for farmers when investing in digital technologies.

(v) Educational Deficits (Factor 5): This factor addressed the lack of digital literacy, concerns about technology functionality and reliability, and the absence of practical application examples. These educational deficits represent obstacles to the implementation of digital technologies and necessitate efforts to improve understanding and knowledge in this area.

(vi) Lack of Infrastructure (Factor 6): This factor dealt with infrastructure deficiencies, including issues with technology or software compatibility and insufficient broadband expansion. The positive correlation between the importance attributed to digital systems and this factor highlighted the critical need for adequate infrastructure to support successful implementation.

These findings provide insights into the current perceptions and realities of digitalization in German agriculture, identifying key areas that need to be addressed to facilitate broader and more effective adoption of digital technologies. While the benefits in terms of efficiency and sustainability are evident, overcoming obstacles such as infrastructure deficits and knowledge gaps is essential for successful implementation. Recommendations include standardizing data, enhancing education and training in digital technology, fostering cooperation among agricultural companies, and establishing clear regulations regarding data protection and usage to promote trust and security in digital systems.

## 4.7 New Digital Technologies

The University of Bremen is a medium-sized institution in Germany, accommodating approximately 18,000 students. It maintains a robust collaborative relationship with 48 non-university research institutes, most of which have been situated on its academic campus since the mid-1980s. Since 2016, 11 of these institutes have received joint funding from federal and state governments. Among them is the BIBA Institute (a private entity), which employs 159 staff members, including scientists, researchers, and administrative personnel. This institute was the second subject of study in this research.

As of April 2024, BIBA is engaged in 40 research projects. The funding model typically involves a combination of resources from the university (and its partner institutions), sponsorships from companies, and grants from innovation incentive programs funded by the German government and the European Union. In addition to research projects, BIBA facilitates numerous technology transfers through published scientific articles, master's theses, doctoral dissertations, and over 50 patents granted from projects initiated at the institute.

Digital technologies are significantly impacting various sectors, including agriculture. This research focuses on analyzing seven projects from BIBA to derive insights and conclusions. These projects are at the forefront of innovation, exploring new digital technologies to address complex challenges across different sectors. Each project encounters specific challenges and presents opportunities for substantial advancements, which are detailed in Table 4.

| PROJECT | DESCRITIVO | CHALLENGES | OPPORTUNITIES |
|---|---|---|---|
| (i) ErgoKI | The ErgoKI aims to develop a system for the acquisition and analysis of ergonomic data in manual assembly, using wearables and mechanical vision techniques. | Integrate multiple sensors accurately in a dynamic manual assembly environment. Develop robust AI algorithms for real-time data analysis. | Enhance understanding of workers' ergonomic requirements. Implement targeted improvements based on AI analyses, resulting in safer and more efficient work environments. |
| (ii) MaxManter | MaxManter aims to develop a control platform for the maintenance of effluent treatment stations, using augmented reality and intelligent scheduling. | Ensure the reliability of AR technologies for remote diagnosis of failures in complex wastewater treatment environments. | Reduce downtime and operational costs through remote monitoring and real-time assistance, thereby improving maintenance efficiency. |
| (iii) Digikleb | The DigiKleb focuses on digitizing adhesive processes in the automotive industry, using advanced process modeling techniques. | Model and accurately predict the behavior of the adhesive system, considering complex interdependencies and process variables. | Quickly identify causes of quality deviations and propose proactive corrective measures, thereby enhancing production process efficiency and quality. |
| (iv) Port2Connect | Port2Connect develops a digital port logbook to enhance the efficiency and sustainability of port processes, using intelligent monitoring systems. | Develop a robust logbook capable of handling adverse conditions in dynamic port environments. | Increase transparency and efficiency of port processes, reducing emissions and protecting infrastructure against damages. |
| (v) Syditil | SYDITIL develops digital twins to optimize logistic processes, using advanced simulations and risk forecasting. | Integrating complex logistics system data into a systemic digital twin, ensuring accuracy and reliability of analyses. | Continuously improve logistics processes through accurate simulations and risk predictions, optimizing operational efficiency and reducing costs. |
| (vi) SafetyDrone | SafetyDrone develops autonomous drones for detecting safety risks in shipbuilding environments, using sensors and AI algorithms. | Develop robust autonomous drones capable of detecting safety risks in dynamic and complex environments. | Increase worker safety through autonomous aerial monitoring and early detection of potential hazards. |

| | | | |
|---|---|---|---|
| (vii) Heatrix | The Heatrix project is an innovative solution for decarbonizing high-temperature industrial heat, developed to reduce CO² emissions in energy-intensive industries. | Design of a system that could provide continuous process heat at high temperatures, reaching up to 1,500°C, while ensuring energy efficiency and competitiveness compared to fossil fuels. Additionally, long-term thermal storage was identified as a necessity to ensure the availability of green heat 24/7, making the technology viable for continuous industrial operations. | By offering green heat without carbon emissions, Heatrix has the potential to revolutionize high-impact environmental industries, aligning with global sustainability and decarbonization goals. Its long-term thermal storage capability also represents a significant opportunity to ensure a continuous supply of green heat, even when renewable energy generation is intermittent. Additionally, the system's efficiency and modularity allow for easy scalability and integration with a variety of industrial processes, opening doors for applications across different sectors. Economically, Heatrix's competitive cost compared to fossil fuels and green hydrogen represents an added advantage, making it an attractive option for companies looking to reduce operational costs and comply with increasingly stringent environmental regulations. In summary, the Heatrix project offers a unique opportunity to transform the industrial energy landscape, promoting the transition to a low-carbon economy and driving innovation in the process heat sector. |

Table 4: International Technology Projects.

This table outlines the new digital technologies being investigated across various projects. These technologies have the potential to significantly impact the grain post-harvest sector by enhancing efficiency in processes such as receiving, cleaning, drying, storage, and shipping, which in turn can affect product quality and operational sustainability.

These projects are shaping the future of the industry and present opportunities for Brazilian companies specializing in post-harvest grain solutions. The adoption of emerging technologies, such as smart sensors, artificial intelligence (AI), and advanced monitoring systems, can improve the efficiency, safety, and quality of post-harvest processes, positioning these companies for a digitally advanced future.

For Brazilian firms in the post-harvest sector, key technological trends include the implementation of remote monitoring systems, the integration of AI and data analysis for process optimization, and the development of innovative, sustainable solutions tailored to local conditions. Furthermore, investing in training and education to effectively utilize these new technologies will be crucial for maximizing benefits and maintaining competitiveness in the global market.

# 5 DISCUSSION

This study examines the effects of digital transformation within the post-harvest sector, drawing on data and information from a specific company in the field. The analysis reveals several key conclusions about the changes brought about by the integration of digital technologies. The company has implemented four primary actions to facilitate digital transformation: (i) establishing technological standards, (ii) enhancing connectivity, (iii) creating a new corporate structure dedicated to digital initiatives, and (iv) pursuing inorganic growth.

While the next step involves managing data and monetizing it through value appropriation, further research is required to explore effective strategies for data monetization. The absence of a specific framework for this purpose underscores the need for clear and effective strategies to maximize the value derived from digital transformation.

To maintain its competitive advantage, the organization must reevaluate and update its value creation and appropriation models. It is also crucial for the company to align its business models with its overall strategy. The rapid pace of digital transformation in post-harvest grain processing necessitates that the company adapt quickly to manage inorganic growth while continuing to deliver impactful and valuable new technology products to its customers. Failure to adapt may jeopardize the company's leadership position and the benefits achieved through its digital transformation efforts.

In summary, the successful development and implementation of a digital transformation strategy require a holistic approach that addresses not only technical aspects but also cultural, financial, and human resource considerations. This complex process demands strategic planning, judicious investment, and a sustained commitment to adapting to market demands and technological advancements.

## 5.1 Impacts on Sustainable Development

Stathers (2020) emphasizes that goals established under the 17 Sustainable Development Goals (SDGs) aim to reduce losses throughout the food supply chain (SDGs, 2015). The reduction of post-harvest food loss has significant implications for various SDGs related to food systems and extends to socio-economic and environmental impacts. Specifically, it affects SDGs 1 (No Poverty), 2 (Zero Hunger and Sustainable Agriculture), 5 (Gender Equality), 6 (Clean Water and Sanitation), 7 (Affordable and Clean Energy), 8 (Decent Work and Economic Growth), 9 (Industry, Innovation, and Infrastructure), 10 (Reduced Inequalities), 11 (Sustainable Cities and Communities), 13 (Climate Action), 14 (Life Below Water), 15 (Life on Land), and 17 (Partnerships for the Goals) (FAO, 2019).

In response to these complex challenges, the organization under study conducted a comprehensive assessment of environmental, social, and governance (ESG) dimensions. This assessment led to the development of initiatives aligned with six of the 17 SDGs set by the United Nations. According to Schmidt (2023), digital technologies have the potential to increase global grain production by approximately 7%. This estimate is based on comprehensive research that analyzed more than 300 cases of post-harvest loss re-duction initiatives, revealing a potential reduction in production losses ranging from 2% to 28%, with an average decrease of around 7% and a standard deviation of approximately 11% (Benyam et al., 2021).

Table 5 presents the SDGs prioritized by the organization. These priorities are directly related to achieving the objectives, with each theme being significantly influenced by the ongoing digital transformation within the company's product portfolio.

| ODS | RECOMMENDED TOPICS | DIGITAL TECHNOLOGIES |
|---|---|---|
| SDG 2 | Waste Management (GR's)<br>Product quality and safety<br>Customer Relations<br>Supplier Management | Automatic systems with a focus on final grain quality, a focus on equipment integrity, offering digital services, active consulting, and component standardization. |
| SDG 16 | Risk Governance, including social, environmental and climate Purpose, values, and organizational culture | Automation and remote monitoring systems. |
| SDG 3 | Occupational Health and Safety | Compliance with regulatory standards (NR's) and automatic systems focused on safety. |
| SDG 7 | Energy Management and Use of Renewable Sources | Automatic systems with a focus on energy efficiency. |
| SDG 8 | Attraction, retention, and professional development | Internal structure focused on research and development of digital technologies for post-harvest. |
| SDG 13 | GHG Emission Reductions, Decarbonization and Climate Change Adaptation | Automatic systems with a focus on energy efficiency. |

Table 5: SDG’s Aligned with Organization's Prioritized Themes.

## 5.2 Theoretical Analysis of the Company's Strategy

The company's strategy is characterized by a strong entrepreneurial orientation. From 2015 to 2023, Kepler Weber S/A made significant strides toward digitalization in the post-harvest sector, achieving remarkable growth. Schwab (2016) discusses how new technologies are changing the way companies operate and emphasizes the need for an entrepreneurial mindset to navigate these changes and explore emerging opportunities.

During this period, the company's management dynamics were predominantly shaped by the entrepreneurial mode of strategy formation. This mode involved the active pursuit of new market opportunities, decisive actions by a strong board of directors, and a focus on business growth and expansion. The expansion of Kepler Weber's business through new digital technology products, acquisitions, and new monetization avenues reflects this entrepreneurial vision, highlighting the company's agility and adaptability in a changing business environment.

The period also saw a pronounced market orientation driven by the pursuit of digital business opportunities, which allowed the company to diversify beyond its traditional metal-mechanical products, such as silos and dryers. Favorable internal conditions, macroeconomic and political stability, and a thriving agricultural sector provided a conducive environment for growth. The company benefited from credit facilities, government incentives, and a receptive market, enabling it to capitalize on these opportunities.

During this phase of growth, Kepler Weber's strategic behavior aligned with Christensen's (1997) disruptive innovation approach, characterized by the continuous search for market opportunities and the expansion of products and services. This approach prioritizes innovation and the introduction of new products, even if not all initiatives are immediately profitable.

Historically, Kepler Weber's top management has embraced diversification to mitigate the seasonality associated with its core products. This diversification strategy was a deliberate decision aimed at expanding the company's presence in the digital segment. According to Porter (1985), diversification is a deliberate strategy aimed at expanding the company's presence in new markets by leveraging interrelationships between related businesses. This approach involves intentional choices by the board of directors, with the goal of increasing competitiveness and efficiency through synergy between existing operations and new market opportunities.

The digital diversification strategy was carefully planned and aimed at integrating new opportunities related to the company's core business in grain storage systems. Porter (1985) emphasizes that a successful diversification strategy hinges on the ability to leverage interrelationships between related businesses. Kepler Weber's strategy illustrates this principle by utilizing digital technologies to create synergies with its existing operations. Porter identifies three types of interrelationships: market, production, and technological. Kepler Weber’s strategy aligns with these types, focusing on digital technologies to enhance market reach, production efficiency, and technological development.

Kanter (2006) discusses the distinction between intentional strategies, which are planned and executed as intended, and strategies that adapt to new circumstances. Kepler Weber’s diversification strategy during the analyzed period was deliberate and planned, rather than emergent or unintended.

## 5.3 Contributions to the Corporate Digital Transformation Strategy

The digital strategy, characterized by horizontal structuring to achieve a competitive advantage as defined by Porter (1985), necessitates maintaining coordination across various business units to exploit new opportunities for digital transformation both within and outside the organization.

This approach has led to significant impacts on the corporate sustainability policy and has generated qualitative outcomes, as revealed through interviews. These impacts focus on value creation for both customers and the organization. However, the implementation of digital transformation faced several challenges. The company’s efforts to advance post-harvest digitization underscore not only the effectiveness of its actions but also the necessity for ongoing adaptation to sustain competitiveness in a market where other players are also striving to establish a presence.

Table 6 outlines the impacts from both a customer and an organization perspective, relating these impacts to the key challenges of the company's digital transformation initiatives. In addition, the table correlates these themes with those challenges identified in digital transformation efforts in the German market.

| PERCEPTION OF VALUE | QUALITATIVE IMPACT | CHALLENGES (BRAZIL) | CHALLENGES (GERMANY), (MUNZ ET AL. (2019) |
|---|---|---|---|
| Customer | Customer Experience | Qualification of the workforce | Educational Deficits |
| ↕ | Grain Quality | Sustainable Product Portfolio | Economic and Ecológicas Advantages |
| | Agility and Flexibility | Technology Cost | Financial Risk |
| | Brand Reputation | ◄ | ► |
| | Product Innovation | Technological and Integration Challenges | Lack of infrastructure |
| Organization | New Business Model | Digital Infrastructure and Strategy Review | Inter-company Coordination |
| | Organization Culture | Cultural and Human Resources Barriers | Socioeconomic Risks |

Table 6: Qualitative Impacts and Relevant Themes.

Table 6 illustrates a notable correlation between the issues addressed in German agriculture and those observed in the company under study. Economic and ecological benefits, such as cost reduction and resource efficiency, identified in German agriculture, align with specific challenges faced by the company, including the need to adapt mechanical designs for automation and to develop more efficient solutions. Additionally, cultural and human resource barriers common to both contexts—such as resistance to change, organizational restructuring, and personnel training for digital transformation—reflect widespread challenges associated with digitization in the agricultural sector, irrespective of geographical or organizational differences.

Financial impacts, as evidenced by the EBITDA margin, indicate a significant shift in the company's market position following the initiation of digital transformation. The profit margins quadrupled after the initial strategic move, and this sustained growth over seven years suggests a strong correlation between digital transformation and financial performance, supporting the effectiveness of the digital strategies implemented. Diversification into digital solutions has generated additional revenue streams, highlighting the strategic significance of this shift for financial growth. Efficiency analyses in grain storage and drying processes further demonstrate tangible benefits for end customers associated with digital technologies. Notably, the reduction in drying losses, particularly relevant in the Brazilian agricultural context, underscores the economic value of these technologies.

On an international scale, the new digital technologies observed at BIBA could significantly impact grain post-harvest solutions by enhancing control, precision, and automation. The company's adoption of industrial technological standards, such as integrating embedded industrial PLCs into its equipment, aligns with practices observed in BIBA's projects. Although prototype development may initially use low-cost hardware, commercial deployment transitions to industrial-grade hardware (e.g., SIEMENS).

Table 7 details the new technologies identified and their potential qualitative impacts on the Brazilian company's post-harvest solutions.

| TECHNOLOGY - BIBA | | IMPACTS – COMPANY (QUALITATIVE) | PROJECT - BIBA |
|---|---|---|---|
| (i) | Sensors and Wearables | Product Innovation | ErgoKI and SafetyDrone |
| (ii) | Computer Vision<br>Artificial Intelligence<br>Machine Learning<br>(PyTorch and TensorFlow) | Grain quality<br>Agility and Flexibility | ErgoKI, SafetyDrone and Digikleb |
| (iii) | Digital Twin | Grain Quality | SYDITIL and Digikleb |
| (iv) | Augmented Reality<br>Virtual reality | Customer Experience | MaxMaintain |
| (v) | Communication Networks<br>Remote Monitoring | Agility and Flexibility<br>New Service Business Model | Port2Connect |
| (vii) | Decarbonization | Product Innovation | Heatrix |
| (viii) | Public-private Partnerships (companies, university and government | Organizational culture | BIBA Institute (Model) |

Table 7: New Digital Technologies.

(i) Sensors and Wearables: Projects such as ErgoKI and safetyDrone utilize sensors and wearable devices to collect ergonomic data and detect safety risks in industrial environments. These technologies can be adapted for monitoring conditions during post-harvest grain handling, enhancing worker safety and process efficiency.

(ii) Computer Vision, Artificial Intelligence, Machine Learning: The ErgoKI project applies AI-based analysis to ergonomic data, while safetyDrone employs AI algorithms for risk detection. The Digikleb project uses machine learning to forecast the efficiency of the gluing process via a digital twin. These capabilities can be leveraged to develop automated monitoring systems for post-harvest grains, facilitating the identification of grain quality patterns, damages, or contaminations. The use of PyTorch and TensorFlow for data analysis in industry projects can similarly advance post-harvest processes.

(iii) Digital Twin: The SYDITIL project creates market-standard software for designing digital twins of industrial logistics. Implementing digital twins for grain drying and storage processes could enable predictive adjustments to operational parameters, improving performance and the quality of processed grain.

(iv) Augmented Reality and Virtual Reality: The MaxManter project uses augmented reality (AR) to assist in fault diagnosis in wastewater treatment stations. These technologies can be employed for remote training of operators in grain storage and processing facilities, enhancing efficiency and reducing downtime.

(v) Communication Networks and Remote Monitoring: Port2Connect develops solutions for digital monitoring of port processes using communication networks and remote monitoring systems. These technologies can be adapted to monitor grain storage silos, providing real-time data on storage conditions and mitigating risks of losses.

(vi) Decarbonization: Heatrix technology presents potential for revolutionizing grain drying by offering a continuous, high-temperature heat source with no $CO_2$ emissions. This technology not only reduces environmental impact but also offers a sustainable and economically viable solution for drying operations. Its flexibility and scalability make it applicable across various production scales, optimizing the entire grain sector value chain from harvest to storage and enhancing product quality and market competitiveness.

(vii) Public-Private Partnership: The projects at BIBA, funded by the university, sponsoring companies, and state innovation incentive programs, demonstrate a successful model of collaboration. Adopting a similar approach in Brazil could drive innovation in the post-harvest sector.

Correlation of Table 6 (Qualitative Impacts and Challenges) with Table 7 (New Digital Technologies) indicates that emerging technological solutions in Germany could address some challenges faced by Brazilian companies in their digital transformation (Figure 5). Adoption of sensors, artificial intelligence, and decarbonization solutions, such as Heatrix, can enhance energy efficiency and sustainability, particularly in grain drying. Augmented and virtual reality technologies can address cultural barriers and improve workforce training, while communication networks and remote monitoring can resolve technological and data integration issues. Integrating these solutions will support more effective implementation of digital transformation for post-harvest solution providers.

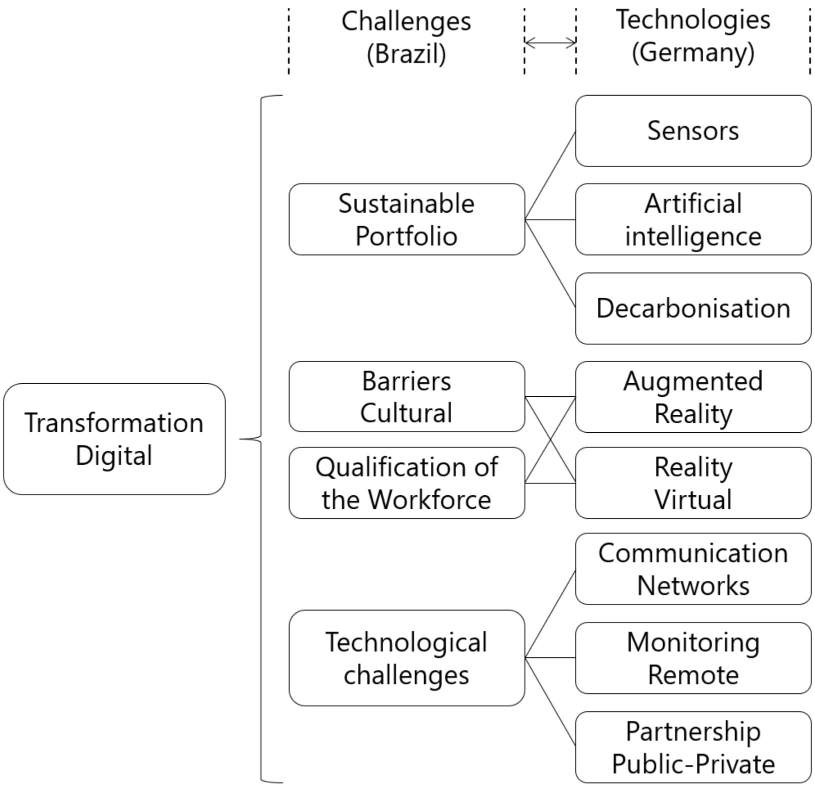



Figure 5: Company Challenges (Brazil) vs. New Technologies (Germany).

The correlation between the two tables emphasizes the significance of collaboration and knowledge exchange among companies and research institutes across different countries. Such cooperation is essential for leveraging best practices and available technologies to foster innovation and enhance global competitiveness.

In the current era of continuous technological advancement, connectivity and data collection are pivotal across various sectors, including post-harvest. The progress in applying machine learning technologies, such as PyTorch and TensorFlow, to projects developed at BIBA illustrates this trend. Despite these advancements, challenges persist. Although artificial intelligence can predict future events, integrating these predictions in real-time with initial processes remains an unresolved issue. This gap impedes organizations from fully realizing the economic benefits of digital transformation initiatives.

Research by Schmidt et al. (2023) introduces a technology platform concept for post-harvest that suggests potential methods for leveraging data for mutual benefit between customers and machines. However, achieving seamless integration between AI predictive data and real-time processes is a challenge that persists in both academic research and industry practice. The projects studied at BIBA did not demonstrate real-time connections between digital twins equipped with AI and the physical world. Nonetheless, ongoing technological development remains crucial for long-term success, and this integration is a goal for researchers interviewed at BIBA. Companies that continue to invest in research and development to address these challenges will be well-positioned to lead their markets.

As artificial intelligence continues to transform interactions between society and machines, the potential for innovation and operational efficiency is substantial. Future advancements are expected to enhance data value capture and expand the benefits of digital transformation. Achieving this will require sustained commitment to technological advancement and a collaborative approach among academia, industry, and governments to address remaining challenges. The journey toward fully realizing digital transformation's potential is ongoing, with considerable and promising benefits on the horizon.

# 6 FINAL REMARKS

The analysis of profit margin increases and the impacts on agricultural communities, operational efficiency, and perceived value reveals that the digital revolution transcends a mere technological transformation. It represents a profound cultural shift that directly influences agricultural systems. This evolution, which extends "from the grain to the cloud," reflects not only adaptation to new technologies but also the leadership required to shape industry trends. Despite challenges and barriers, a strategic vision allows these obstacles to be transformed into opportunities.

Value creation, identified as the primary objective of digital transformation, was clearly demonstrated through both qualitative and quantitative analyses. The results indicate a positive alignment between organizational goals, market demands, and the tangible benefits derived from the integration of digital technologies.

Considering the growing shortage of qualified labor and the complexity of managing storage units, it is essential for clients to invest in digital technologies to maintain operational efficiency and sustainability. The labor shortage highlights the need for technological solutions to fill this gap. Additionally, technology plays a vital role in reducing post-harvest losses and preserving grain quality, which are critical factors for market competitiveness and profitability. Investing in digital solutions not only enhances operational efficiency but also strengthens clients' ability to address the emerging challenges in the sector, positioning them as innovative and sustainable leaders.

The company must update its strategy, focusing on the creation and appropriation of value through digital technologies to achieve its long-term objectives. The digital strategy should also consider external environmental factors, the technological potential within the competitive landscape, and market evolution. Identifying the necessary modifications in the business model and clearly defining the scope of the digital transformation are essential steps to maintaining the company’s leadership and progress.

However, it is crucial that the company does not hand over the full potential value to be captured from digital transformation to the acquired technological player, risking the loss of competitive advantages that the technology provides. The company must be proactive in exploring the value of the technology independently. If the company simply waits for the player to deliver the benefits without taking strategic action, the gains may be limited to indirect outcomes, restricting the company’s ability to fully capitalize on the value generated. Therefore, it is essential that the acquired technology is actively integrated into the company’s portfolio, enabling it to differentiate itself in the market through innovative use of the technology, rather than merely through the inorganic growth of the acquired player.

Proper integration of the organizational structures, processes, and cultures of both companies is crucial for the technology to become a true competitive differentiator. The value generated by the technology must be directly reflected in the company's operations, strengthening its market position and transforming the acquisition into a strategic advantage.

The results also highlight the impact of these innovations in reducing energy consumption, improving grain quality control, ensuring process efficiency, and enhancing food safety. In the drying process, identified innovations demonstrate potential operational gains estimated at USD 700 million annually in Brazil. Moreover, the research shows that these innovations can generate both quantitative and qualitative economic value, benefiting not only the post-harvest sector but the entire agricultural supply chain.

The primary implication of the research is the need to create an internal digital structure, essential for the success of the digital transformation. Acquiring a technological player should be part of a broader strategy that minimizes dependence on external suppliers, ensures greater control over innovations and costs, and, most importantly, integrates the technology into the company's portfolio to differentiate it in the market.

Emerging technologies observed in Germany stand out as relevant for addressing the challenges of digital transformation and guiding corporate strategies. This work offers valuable insights for companies and researchers seeking to explore the opportunities of digitization in the post-harvest grain sector, with a focus on economic and efficiency gains in drying and storage units.

Future research can expand these findings by exploring the long-term effects and practical frameworks for implementing digital strategies. The emerging technologies observed in Germany provide a clear vision of future innovations, suggesting a continuous evolution that not only keeps pace with changes but also leads the digital transformation in agriculture. The digital revolution in post-harvest grain processing represents the starting point for a future where innovation, sustainability, and value creation converge.

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# 6 FINAL REMARKS

This dissertation analyzes the opportunities and challenges associated with digital transformation in the context of post-harvest grain solutions, exploring these aspects through three interconnected approaches: a bibliometric analysis, a case study of a Brazilian company, and an international empirical survey.

The research findings highlight the importance of technologies such as automation systems, artificial intelligence, and sensors to optimize cleaning, drying, and storage operations for grains. Each post-harvest stage was carefully analyzed, identifying digital technology solutions with the greatest potential to reduce losses and increase efficiency. These findings provide a strategic foundation for the development of new solutions specific to each phase of the process, driving advances in quality control and loss minimization.

Additionally, the research emphasizes that the implementation of digital technologies in grain storage units (GSUs) is essential to reduce qualitative and quantitative losses at nine critical control points, from reception to shipping. During storage, dry matter losses can reach 0.3% per month. Real-time sensors that monitor humidity, temperature, and climatic conditions enable more effective management of cleaning, drying, and storage, preventing deterioration. The research revealed that these digital technologies could reduce grain losses by up to 7%, promoting greater efficiency in the process.

The adoption of these innovations affects energy consumption reduction, improves quality control of grains, ensures process efficiency, and increases food safety. In the drying process, the identified innovations demonstrate an estimated operational gain potential of $700 million annually in Brazil. Furthermore, the dissertation illustrates the ability of these innovations to generate economic value, both quantitative and qualitative, benefiting not only the post-harvest sector but the entire agricultural supply chain.

The case study conducted with the Brazilian company reveals important insights about the crucial role of the internal structure focused on digital in its digital transformation. The creation of this specific structure bridges the gap between product development and information technology (IT), allowing greater integration between teams and the necessary synergy for the successful implementation of digital innovations. This finding is extremely relevant, reinforcing not only the importance of a structured approach to digital transformation but also pointing to a fundamental technical and managerial implication: the need to strengthen internal digital capabilities to ensure the continuity and effectiveness of the transformation process.

Another important aspect identified in the case study was the strategic acquisition of a technology player by the company. This move played a crucial role in minimizing dependence on external suppliers, reducing the risk of exposure to future issues, such as limited innovation or rising supply costs. The ability to control key technologies emerges as an essential managerial recommendation for companies seeking to strengthen their independence and ensure the sustainability of their digital operations in the long term.

However, it is critical that the company does not solely rely on the acquired technology player to capture the potential value of digital transformation, as this can result in the loss of competitive advantages. The company should adopt a proactive stance through its internal digital structure in exploring the value of this technology, rather than passively waiting for the benefits that the player may provide. Without a clear strategy, gains tend to be limited to indirect results of inorganic growth, restricting the company's ability to fully leverage the generated value. Actively integrating the technology into the portfolio will allow the company to stand out in the market through its innovative use, rather than relying solely on the expansion provided by the acquisition.

The proper integration of organizational structures, processes, and cultures of both companies is crucial for the technology to become a true competitive differentiator. The value generated by technology must be directly reflected in the company's operations, strengthening its market position and transforming the acquisition into a strategic advantage.

In the international context, the empirical research conducted in Germany identified emerging technological trends that play a relevant role in overcoming the challenges of digital transformation and guiding corporate strategies. International collaboration and knowledge exchange emerge as promising ways for Brazilian companies to overcome common barriers, such as systems integration and personnel training.

The theoretical implications include expanding the understanding of digitization in the agricultural sector and the role of emerging technologies in digital transformation. For engineering solution providers, digitization offers a competitive advantage, while society benefits from improved food safety and quality.

While the dissertation presents significant contributions, it is necessary to acknowledge some limitations. The single case study may restrict the generalization of findings, and the bibliometric analysis may not fully capture emerging technological trends. Moreover, the comparison between Brazil and Germany reflects cultural and contextual differences that should be explored in future research.

Future studies should focus on the integration of systems throughout the post-harvest value chain, aiming to increase interoperability and efficiency. Further research on innovative business models and international collaboration strategies may provide new insights. Investigating the social, economic, and environmental impacts of digital transformation can also guide public policies and more sustainable practices.

In summary, this dissertation significantly contributes to understanding the role of digital technologies in the post-harvest grain sector. The results provide a solid foundation for advancing digital transformation in the sector, offering valuable insights for companies, researchers, and policymakers. The research emphasizes the broad benefits of these technological innovations, highlighting the importance of a robust internal digital structure and technological independence for the continued success of companies.

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