


## Article

# Digital Technologies, Sustainability, and Efficiency in Grain Post-Harvest Activities: A Bibliometric Analysis

Daniel Schmidt <sup>1</sup>, Luis Fernando Casagrande <sup>1</sup>, Maria Angela Butturi <sup>2</sup> and Miguel Afonso Sellitto <sup>1,\*</sup>

<sup>1</sup> Production and Systems Engineering Graduate Program, Universidade do Vale do Rio dos Sinos (UNISINOS), São Leopoldo 93022-000, Brazil; daniel.panambi@gmail.com (D.S.); fernando@tecnoflex-rs.com.br (L.F.C.)

<sup>2</sup> Department of Sciences and Methods for Engineering (DISMI), University of Modena and Reggio Emilia, 42122 Reggio Emilia, Italy; mariaangela.butturi@unimore.it

\* Correspondence: sellitto@unisinos.br

**Abstract:** Post-harvest grain processes play a crucial role in food supply chains. Recent research focuses on how digital technologies can minimize grain losses, enhance food safety, and reduce their environmental impacts. The relationship between technologies and efficiency and sustainability needs more clarity, 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 literature survey identified thirteen digital technologies. The most published technologies are simulation, automation, and artificial intelligence. The least is augmented reality. Previous research identified nine critical control points in post-harvest engineering solutions, responsible for most losses in efficiency and environmental impacts. A framework using a sample of recent case studies was constructed to relate digital technologies and critical control points. The primary contribution of the study is 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 selection of technologies for future projects. Ultimately, this aids in reducing losses and environmental impact.

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



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## 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 [13–15]. Concerning the grain quality, the primary focuses include moisture control, insect infestation, and toxin contamination [16–18].

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 gap 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.

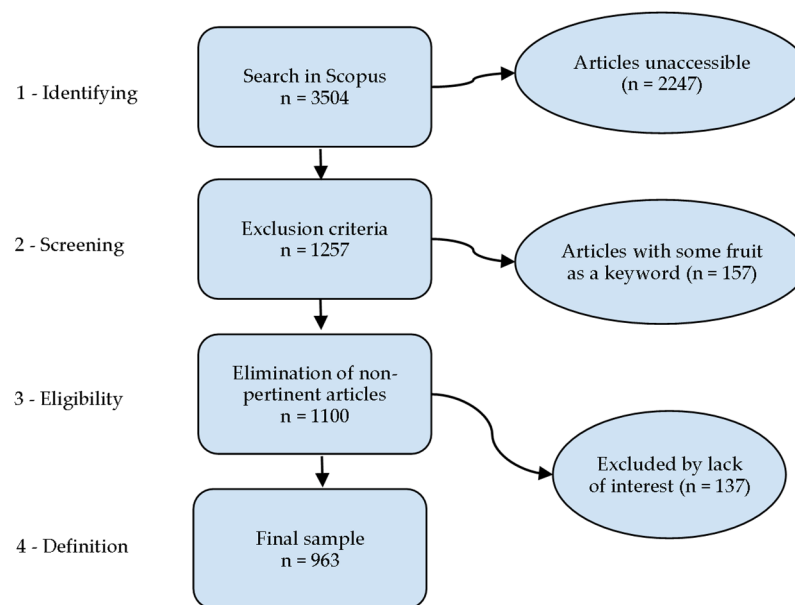
This study utilized data from Scopus articles on digital transformation in post-grain harvest due to the extensive title availability. Other databases like EBSCOHost and CAPES lacked significant contributions. Research keywords were established based on diverse digital technologies relevant to the post-harvest 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.

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.

**Table 1.** Attributes and filters for the bibliographic search.

Attribute	Filter
Search base	Scopus
Year	Up to 2022
Author name	No filter
Search area	No filter
Document Type	Limited to Articles
Country	No filter
Research field	Any field
Language	English



**Figure 1.** Flowchart of the bibliographic search.

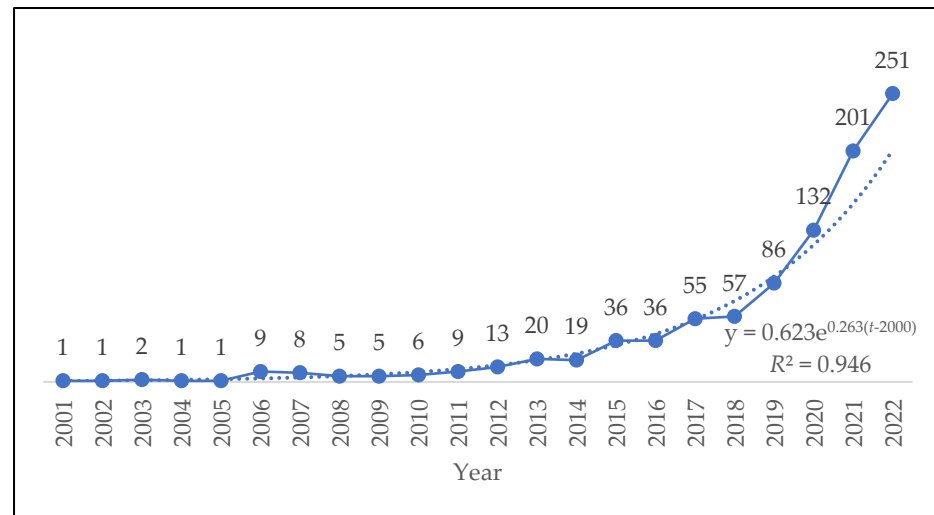
After the bibliometric analysis, three experts helped to identify how each technology can contribute to improving efficiency and sustainability in grain post-harvest activities.

### 3. Results

#### 3.1. Bibliometric Analysis

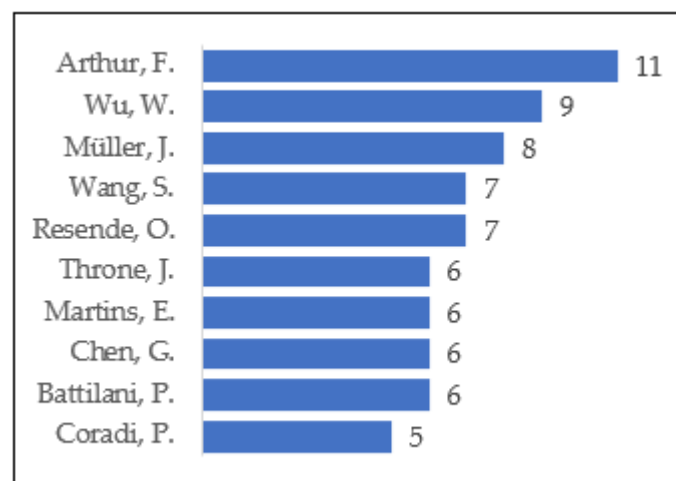
Despite some isolated early articles, publication was enhanced after 2001. An exponential model applies to the growth in publications. An initial article authored by Reutlinger in 1976 introduced a statistical simulation model assessing the influence of storage capacity levels and associated policies 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.



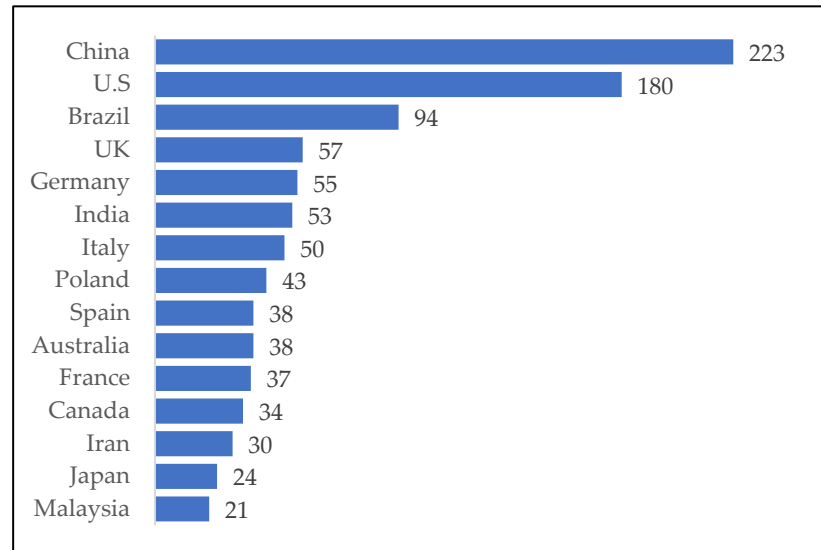
**Figure 2.** Number and trend of retrieved publications per year.

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.



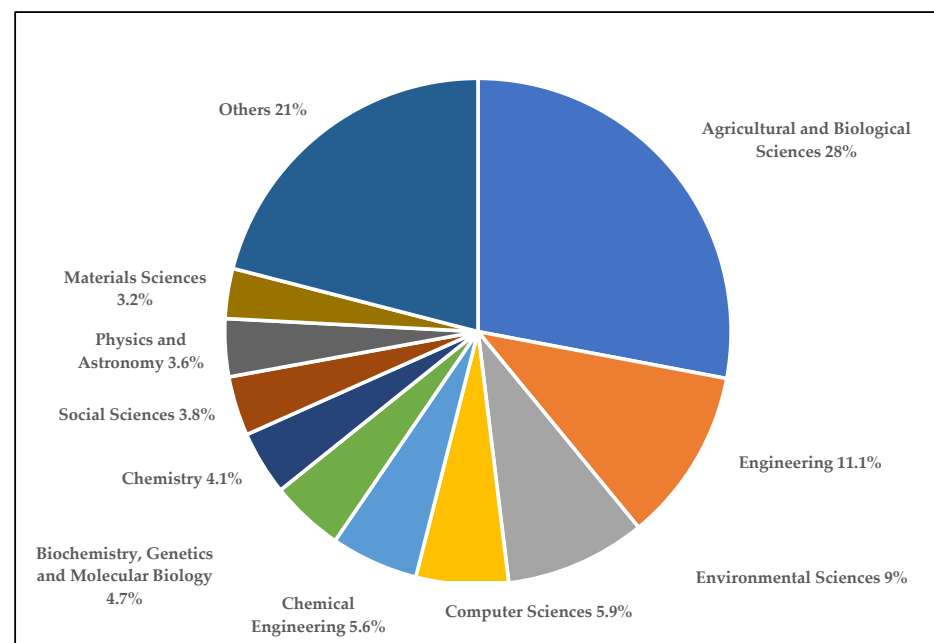
**Figure 3.** Number of retrieved publications per author.

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.

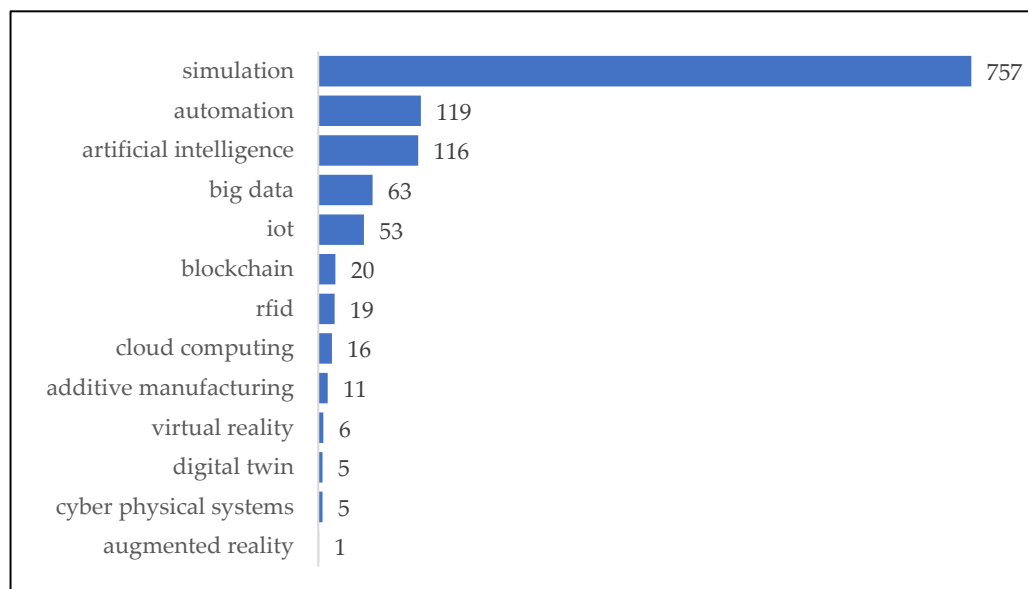
The analysis highlights the top 10 pertinent areas. Agricultural and Biological Sciences lead with 28% of publications, followed by Engineering at 11.1% and Environmental Science at 9%. Together, the three areas constitute nearly half of the articles, encompassing 48.1% of all published content. The 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.



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.

**Table 2.** Most cited article for each technology.

Technology	Article	Citations by July/2023	Citations per Year
Simulation	[25]	389	389
Automation	[26]	102	34
Artificial Intelligence	[27]	303	60.6
Big Data and CC	[28]	161	53.7
IoT	[29]	55	27.5
Blockchain	[30]	64	32
Rfid	[31]	40	13.3
Additive manufacturing	[32]	12	3
Virtual reality	[33]	12	3
Digital twins	[34]	1	1
Cyber-physical systems	[35]	21	10.5
Augmented reality	[36]	2	2

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 security, particularly in cereal production. Enhancing food security 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 security 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 security 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 are 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.

**Table 3.** Relationship between technological solutions and critical control points.

CCP	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]

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. Simula-

tion, 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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