Digital Twins Application in The Post-Harvest Supply Chain of Fruits and Vegetables: A Systematic Review of The Literature

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Abstract

The paper focuses on the use of digital twins as a tool to assist in the management of fruits and vegetables supply chains. Problems such as the perishability of food, the complicated coordination between the different actors in the chain, the lack of traceability of products and the demanding quality requirements for their final consumption are part of a long list of factors that must be considered for the analysis of this work. The methodology used was a systematic review of the literature related to the use of digital twins in supply chains. For this purpose, many papers were collected from the most important databases such as Scopus, Web of Science and Proquest. A total of 59 papers were obtained and used for the writing of this paper. For the analysis of information, the data obtained were categorized into factors and dimensions. The 3 factors identified are: pillars of the perishable food supply chain, technological component and finally organization and coordination of the chain. For the findings section, the VosViewer software was used. It was evidenced that digital twins bring a benefit to each factor mentioned in the study.

Keywords
Digital Twins, Supply Chain Management, perishable food, industry 4.0, food loss

1. Introduction
This study focuses on the analysis of one of the tools that has been acquiring greater relevance in the context of Industry 4.0 in recent years: the digital twins. The main objective of the text is to identify the benefits that can involve the implementation of this technology in the food sector, specifically in the supply chains of fruits and vegetables. Food loss is one of the most significant problems still experienced by various supply chains around the world. According to the Food and Agriculture Organization of the United Nations (FAO 2021), it is defined as "the decrease in quantity or quality of food resulting from the decisions and actions of food suppliers in the chain, excluding retailers, food service providers and consumers". One of the main reasons why it is more viable to focus on reducing food loss than increasing production in the short or medium term is that its solution is not directly constrained by available land and water resources (Alamar et al. 2018). For this, the agricultural sector must study methods to improve productivity, reduce waste and increase traceability (Verboven et al. 2020). These losses are often caused by problems such as the deterioration of perishable crops in the hot and humid climate of many developing countries, seasonality, which causes unsaleable surpluses (Mahajan et al. 2017), and various other factors that occur in fresh food supply chains.

Shelf life plays a key role in the analysis of these types of chains, as food properties degrade over time (Shahbazi & Byun 2020). The perishability of fruits and vegetables is mainly due to their high-water content and their continuous active metabolism after harvesting, which generates a need to accelerate processes among different actors to maintain food quality (Mahajan et al. 2017). Added to the problem of perishability is the factor of the enormous variability that exists between foods, as each fruit and vegetable behaves differently, with different degradation times and reactions to the climates and environments they endure throughout the processes. For this reason, it is essential to try to achieve a total integration of the supply chain, which becomes complicated given the environmental uncertainty, the complexity of the market and the process, the need to coordinate between a large set of heterogeneous actors and multiple operational and regulatory objectives (Ramirez et al. 2021). Also, in the context of the COVID-19 pandemic, human resources and capacity in the transport sector were reduced, and uncertainty in shipments increased as delivery times were altered, thus changing the overall distribution times in the chain. Moreover, in third world countries, the main difficulties in the chain are poor infrastructure and management, low technology deployment and lack of investment in food production systems (Kayikci et al. 2020).

The concept of Digital Twin has gained importance in recent years and has been positioning itself as the alternative of the future to streamline the performance of global supply chains. Some definitions agree that it is a digital replica of a real object or operational process, which reflects its behavior and states throughout its life in a virtual space, connected through data obtained from sensors and advanced "big data" analysis tools (Verboven et al. 2020; Verdouw et al. 2021). IBM (2017) defines 3 fundamental phases in the creation of these twins: the design phase, the construction phase and the operations phase. It further argues that it is critical to apply analytics at all stages. Other definitions postulate this technology, specifically the twin of a food, as a mathematical model that combines factors of its chemical composition and its technological-functional and organoleptic properties (Nikitina et al. 2020), which can be represented through the use of augmented reality (AR) or virtual reality (VR) for end users to examine the 3D model from a computer. The importance of their use in the food sector lies in the fact that they allow data analysis and monitoring of complex systems, online or offline, in order to make predictions, thus achieving more efficient processes to prevent time, money and quality losses (Karadeniz et al. 2019). Moreover, they allow obtaining the degree of compliance with the production plan of a facility in a short time, unlike traditional methods (Nikitina et al. 2020).

1.1 Objectives

This paper seeks to create a framework to guide future research and to bring researchers closer to the implementation of this tool in the industry. For this, the following research question is formulated: How can digital twins contribute to mitigating food loss in perishable food supply chains?

2. Methods

The methodology used in this research is based on a systematic mapping of the literature relevant to digital twins and supply chains. The main reason why this methodology was selected is that to date there is no precise information about the application of this technology in the field of supply chains or the food industry, and, in turn, most of the publications associated with these topics are scattered among different high-impact journals without a clear correlation between them. Figure 1 describes the step-by-step methodology used.

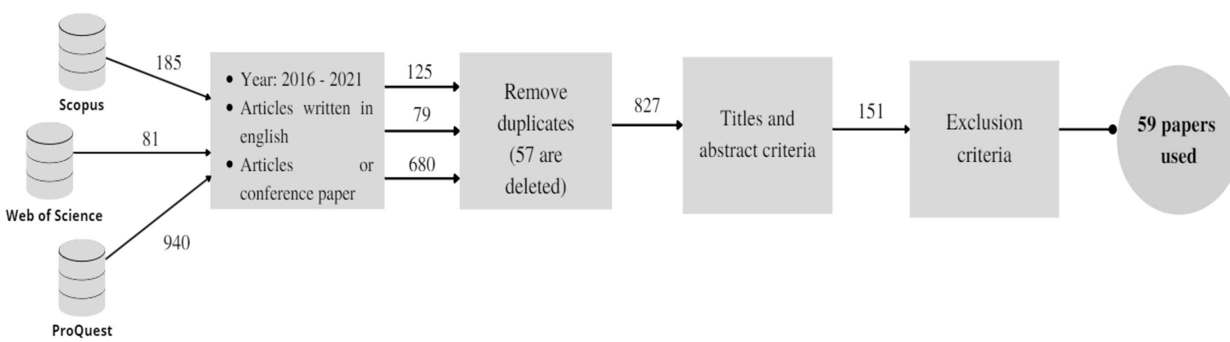

Figure 1. *S*ystematic mapping sequence

The first step was to find the universe of studies in the review by using 3 search strings, which are detailed in Table 1.The search was carried out in 3 databases: Scopus, Web of Science and ProQuest. A total of 1206 results were obtained, and from these it was decided to continue only with those that were published in the period between 2016 and 2021, that were in English and that belonged to the typology of article or conference paper. After refining this search, the duplicates that had been generated in the 3 databases were eliminated. The third criterion consisted of a detailed analysis of the titles and abstracts of each publication. This sweep was very significant, as 81.74% of the papers included in this step were eliminated. Finally, 3 exclusion criteria were applied, detailed in Table 2, to obtain a final sample of 59 papers, which best represents the 3 factors into which this research is divided: the pillars of the perishable food supply chain, the technological component, and finally, the organization and coordination of the chain.

Table 1. Search strings

N°	String
1	(“digital twin” AND “supply chain”) OR (“digital twin” AND “perishable food”) OR (“digital twin” AND “food loss”)
2	(“supply chain” AND “perishable food” AND “food loss”)
3	(“digital twin”) AND (“food”)

Table 2. Exclusion criteria

Criteria	Definition
C1	Articles focused on the study of a specific sector other than the food sector
C2	Articles focused on the post-retail stage of the supply chain
C3	Items that do not contribute to any stage of the supply chain

The following is a detailed description of each of the factors into which this research has been divided and classified.

Pillars of the perishable food supply chain
This factor refers to the intrinsic characteristics of perishable foods and their supply chains, among which three main ones stand out: control of perishability, traceability and control of variability. Perishability is an inherent characteristic of fruits and vegetables, and it complicates supply chain management considerably because it shortens reaction times. Traceability has become a necessity for food companies, which want to transparently track their products for their own management and to improve customer service. In the case of variability, this dimension needs to be studied to understand that different food chains differ from each other and have different control needs.

Technological component
This factor has been considered since it is necessary to explain how technologies are applied in the different stages of the chain, and in turn to understand the relationship between the different technologies that are part of Industry 4.0 and how they relate to the digital twins to generate effective solutions. Three dimensions are distinguished in this case: the related technologies of Industry 4.0, the technology in the logistics stages and the technology in the cold chain. The first dimension alludes to tools such as blockchain, IoT platforms, big data analytics, etc. The second comprises digital twin technologies applied to the different stages of the chain, such as transportation, storage and production. The third deals with the cold chain separately since its importance in perishable food chains is remarkable and there is a need to analyze it individually.

Chain organization and coordination
This factor describes the characteristics related to supply chain management. It is divided into 3 main dimensions: decision support, organizational resources and chain integration. Decision-making is the fundamental consequence of the application of any technological tool in business. The resource dimension refers to the requirements of companies for the implementation of digital twins. As for the third dimension, it deals with the integration between supply chain actors at all levels.

3. Findings
In table 3, the 10 journals with the highest impact included in the study are presented below in descending order of importance, according to the SCImago Journal Rank (SJR) as of 2020. In addition, the highest quartile achieved by the journal, its respective Hirsch index and the average number of citations achieved in 2020 per paper published between 2018 and 2019 are presented, the latter indicator being, for various sources, the impact factor of a journal.

Table 3. Highest impact journals included in the study

Journal	SJR	Best quartile	H-index	Cites / Doc. (2 years)
Trends in Food Science and Technology	2,676	Q1	188	11,9
Resources, Conservation and Recycling	2,468	Q1	130	9,93
Business Strategy and the Environment	2,123	Q1	105	8,99
Journal of Industrial Information Integration	2,042	Q1	24	12,26
Journal of Cleaner Production	1,937	Q1	200	9,56
Agricultural Systems	1,694	Q1	107	5,52
Decision Support Systems	1,564	Q1	151	7,04
Production Planning and Control	1,331	Q1	76	6,79
Current Opinion in Food Science	1,297	Q1	38	5,16
Journal of Food Engineering	1,291	Q1	179	5,41

Figure 2 and Figure 3 break down the universe of the 59 articles considered in this research according to some relevant metrics.

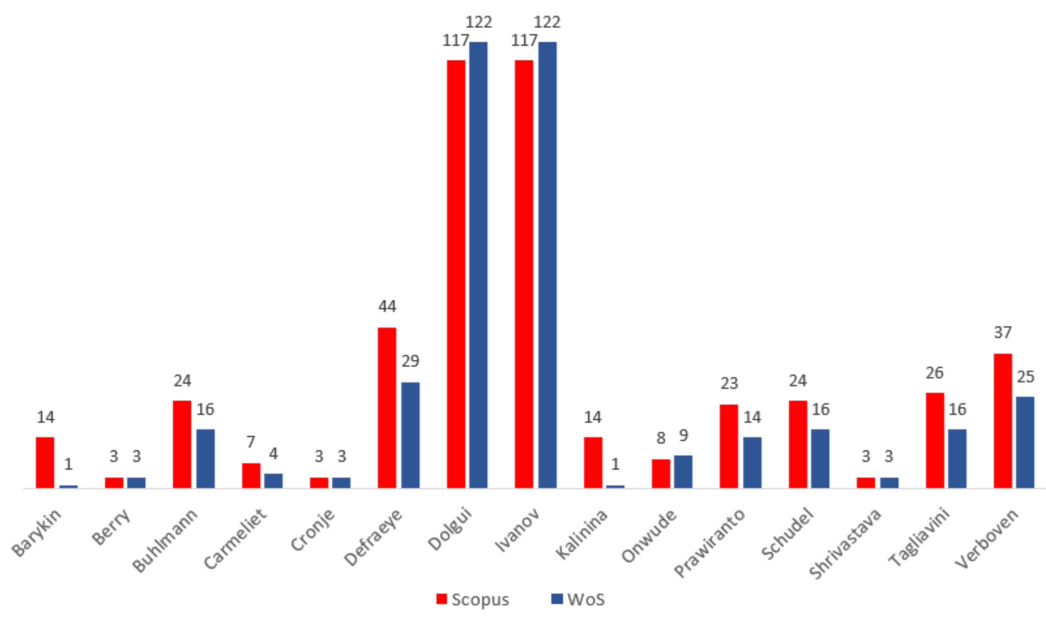

Figure 2. Number of citations per database of authors with more appearances in the sample

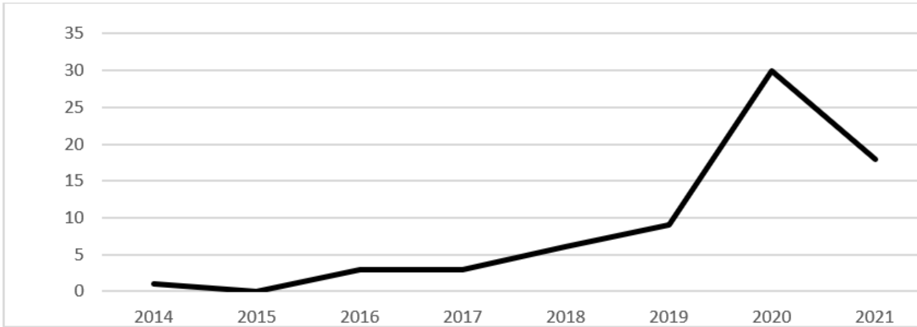

Figure 3. Number of publications per year

The main thematic axes identified in the 59 papers were captured. To find this information, the VosViewer software was used, which allows a qualitative analysis of the key terms and their visual representation by means of a graph. Of the sample of 59 articles analyzed, 53 key terms were found to appear more than 3 times among the keywords or titles of the articles. The most important ones for the study appear among the main ones, with more than 25 appearances and links each. In addition, as shown in Figure 4, the digital twins and their cluster are related to the supply chain and this, in turn, is closely related to food quality and safety; agriculture; harvesting; logistics; trends and mathematical models. Likewise, when looking at cluster 2 in green, the digital twins are related to computational simulation, industrial plants, industrial applications, simulation, optimization, factories, collaboration and manufacturing. On the other hand, analyzing clusters 3 and 4, supply chain and digital twins are also related to big data, decision making, environmental studies, innovations, product life cycle, sustainability, automation, competitive advantages, internet of things, value chain, supply chain management, data analysis and business and economic management.

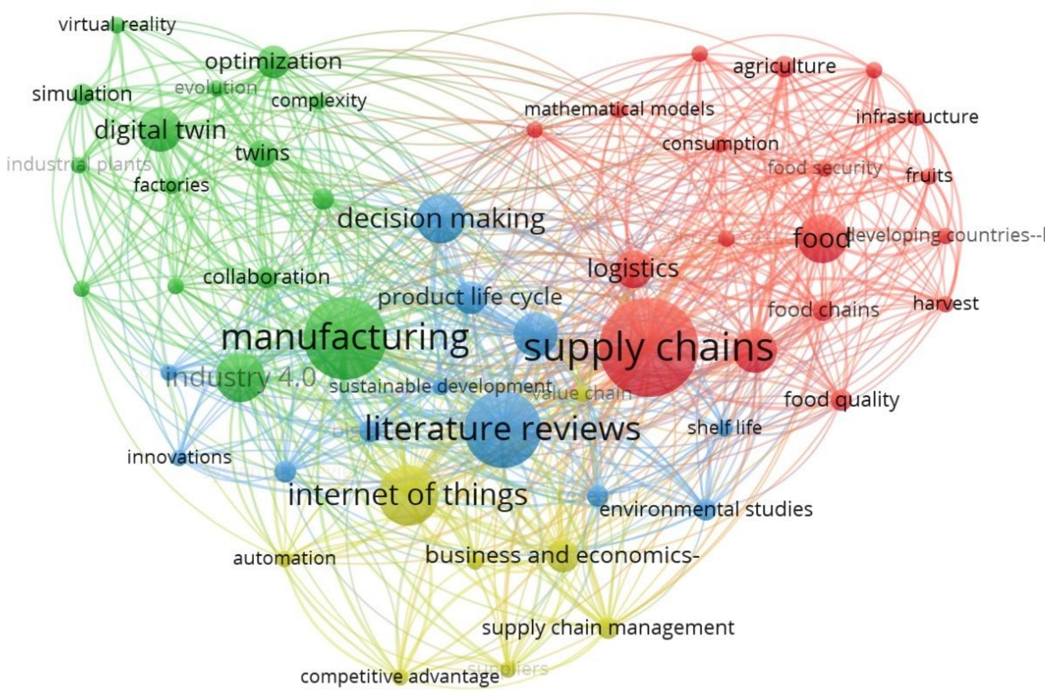

Figure 4. VosViewer for keywords

Table 4 shows the findings from the literature review of the 59 sources considered in the study. The findings are divided according to factor and dimension, in addition to the authors contributing to each division indicated.

Table 4. Literature review findings

Factor	Dimension	Authors	Findings
	Perishability control	(Defraeye et al. 2021); (Onwude et al. 2020); (Shrivastava et al. 2020); (Prawiranto et al. 2021); (Tagliavini et al. 2019); (Pattanaik and Jenamani 2020); (Koulouris et al. 2021); (Gunasekera 2017); (Jedermann et al. 2014); (Singh et al. 2018); (Lorite et al. 2017)	- A mechanistic model should be used - Allow modelling of changes in weight, shelf life, nutritional qualities, pH, water activity, temperature, cold damage, risk of infestation, thermal properties. - Model must consider respiratory activity, structure and distribution during storage in containers or pallets.
	Traceability	(Ivanov and Dolgui 2020); (Frankó et al. 2020); (Srai et al. 2019); (Lorite et al. 2017); (Kayikci et al. 2020); (Shahbazi and Byun 2020); (Defraeye et al. 2019); (Defraeye et al. 2021); (Chisenga et al. 2020); (Bécue et al. 2020)	- Digital twins enable full chain visibility to improve chain resilience - Digital twins combined with RFID or blockchain technology fused with sensors and IoT architecture for real-time monitoring - Ability to non-intrusively monitor trucks, coolers or pallets - Human factor must be considered
	Variability control	(Jakhar and Srivastava, 2018); (Kumar et al., 2020); (Tagliavini et al. 2019); (Defraeye et al. 2021); (Onwude et al. 2020); (Pattanaik and Jenamani 2020); (Shrivastava et al. 2020)	- Need for customised solutions per food type for cold storage and refrigerated movement - Model must consider intra-product chilling, quality, geometry, structure, composition - Must quantify how statistical variability, as a result of biological variability, propagates into model outputs
Technological component	Related technologies of Industry 4.0	(Cañas et al. 2020); (Kuehn 2018); (Tiwari 2020); (Busse et al. 2021); (Verdouw et al. 2021); (Moshood et al. 2021); (Haji et al. 2020); (Onwude et al. 2020); (Ghandar et al. 2021); (Delfino et al. 2019); (Jiang et al. 2021); (Yildiz et al. 2021); (Verboven et al. 2020); (VanDerHorn and Mahadeyan 2021); (Jagtap et al. 2020); (Bécue et al. 2020)	- An integrated IoT architecture should be considered mainly for connectivity and analytics using big data tools. - Machine learning algorithms for anomaly detection in the model - Cloud computing and artificial intelligence for 2D and 3D visualisation of the chain or asset model - Blockchain as a secure and encrypted business-to-business communication tool - Industrial IoT through 5G and edge computing - Digital twin adapted to a Cyber-Range to counter cyber-attacks

	Technologies in the logistic stages	(Pylianidis et al. 2021); (Verdouw et al. 2021); (Defraeye et al. 2021); (Wang et al. 2020); (Jedermann et al. 2014); (Busse et al. 2021); (Orjuela-Castro et al. 2019); (Frankó et al. 2020); (Roy et al. 2020); (Ameri and Sabbagh 2016); (Yildiz et al. 2021); (Pawlewski et al. 2021); (Kalsoom et al. 2020); (Ejsmont et al. 2020); (Roy et al. 2020); (Delfino et al. 2019); (Prawiranto et al. 2021); (Kapustina et al. 2020)	- Complexity in use of digital twins in agriculture due to system dynamism, poor rural connectivity, level of granularity and costs - Digital twins allow farmers to control production remotely, perform simulations and capture information imperceptible to human senses. - In storage, allow evaluation of pre-cooling protocols or facility design, aggregate demand planning, adoption of FEFO system for inventory management. - In transport, real-time monitoring and development of routing models. - In processing or production, they facilitate mass individualisation, maintenance plans, real-time performance and lead to the emergence of digital factories.
	Technologies in the cold chain	(Balaji and Arshinder 2016); (Canali et al. 2016); (Kumar et al. 2020); [Defraeye et al. 2019); (Tagliavini et al. 2019); (Defraeye et al. 2021); (Shrivastava et al. 2020); (Onwude et al. 2020); (Singh et al. 2018)	- Possibility of placing sensors at critical points on containers or pallets to measure temperature or humidity. - In-transit interventions on refrigerated containers - Integration with IoT sensors for real-time monitoring and improved shelf-life predictions
Chain organization and coordination	Decision-making support	(Ivanov and Dolgui 2019); (Barykin et al. 2020); (Kalsoom et al. 2020); (Lutters 2018); (Jagtap et al. 2020); (Singh et al. 2018); (Kuehn 2018); (Bécue et al. 2020); (Moshood et al. 2021)	- Digital twin provides predictions on equipment or supply failures, supplier information and hotspot information - Can be integrated with artificial intelligence and the company's human intellect to strengthen decision making - Effect's analysis using virtual models based on iterative simulations
	Resources in the organization	(Kumar et al. 2020); (Gunasekera 2017); (Jakhar and Srivastava 2018); (Asdecker and Felch 2018); (Singh et al. 2021); (Reeves and Maple 2019); (Ali and Aboelmaged 2021); (Lim et al 2019); (Annese et al. 2014); (Negi and Wood 2019); (Chisenga et al. 2020)	- Need to integrate and train farmers, improve cold-chain infrastructure, standardise information - Barriers such as technical and practical knowledge of workers, time and cost associated with high performance IT infrastructure, lack of inter-firm collaboration and organisational inertia. - Need for a sensor network
	Supply chain integration	(Tiwari 2020); (Kayikci et al. 2020); (Jagtap et al. 2020); (Zhu and Krikke 2020); (Ali and Aboelmaged, 2021); (Kapustina et al. 2020); (Ameri and Sabbagh	- Blockchain as an integration mechanism - Digital platforms for real-time connection and exchange of information and capabilities between suppliers and customers. - Digital twin enables holistic real-time integration of assets, business, processes, etc.

		2016); (Verdouw, 2021); (Shevtshenko et al. 2020); (Reeves and Maple 2019)	

4. Discussion

The findings from the sources considered in the study allow us to address the research question. The analysis of the findings is carried out according to the 3 factors previously mentioned.

Regarding the information relevant to the pillars of the perishable food supply chain, it is evident the need to use mechanistic models to represent in silico all the properties relevant to the nature of fruits or vegetables, which can be influenced by other statistical or data-driven models to obtain more accurate and consistent simulations and results. Furthermore, without the use of such models, it would be impossible to accurately and quickly predict the variables that lead to food loss during the supply chain, as it would not be possible to analyze and determine the critical points for each food group in order to generate efficient mitigation strategies. In addition, studies show the importance of incorporating tools such as RFID and blockchain, coupled with an IoT architecture that contemplates the use of sensors, to be able to track in real time the various batches and even modify the environmental conditions of containers or vehicles as appropriate.

In terms of information relevant to the technological component, each tool that is part of Industry 4.0 can contribute to the design of a structure based on a digital twin of the supply chain. Big data analysis tools make it possible to collect the huge amounts of data generated by the various parties involved about the points where losses are generated, which, through the use of blockchain, can be used for the traceability of food and the exchange of information between companies in a reliable manner. Machine learning and deep learning algorithms make it possible to find information scattered in the data to enrich computational models and improve the quality of predictions. Virtual and augmented reality tools make it possible to inspect 2D or 3D models for graphical visualization of the models (of the food as well as the overall chain), and all this requires an IoT architecture so that the parameters collected with sensors during harvesting, food transport, processing and storage (the entire cold chain) can be connected to the virtual platform in real time and thus constantly act on the drivers of food losses. In addition, virtual factories appear as an inevitable reality in the future.

In terms of information relevant to the organization and coordination of the chain, the digital twin allows immediate and remote decision making, integrating artificial and human intelligence for the analysis and control of parameters. In addition, since they allow a better global and unified visibility of the chain, decentralized decisions can be made together with the other companies as strategic partners, in an iterative way and generating virtual scenarios that allow simulations at graphical and interactive levels to reach highly accurate decisions. For this, the integration of the different actors that are part of the supply chain is fundamental, as the transparency of information allows the alignment of systems and the scaling of solutions to global levels. However, it cannot be overlooked that it is necessary for companies to have trained and motivated personnel, high-performance technological infrastructure, adequate and modern transportation infrastructure, and customized cold chain infrastructure. Furthermore, proportionality is observed between the number of processes included in the digital twin model and the degree of integration achieved with the probability of successful implementation.

Limitations and future research

The requirements for the implementation of a digital twin generate a gap between technologically and economically highly developed organizations and small and medium enterprises. Although there are suppliers of digital twins and open-source applications around the world, there are no facilities for its implementation, so it is not shown as an affordable technology and generates disinterest in organizations towards digital transformation through digital twins. Consequently, companies with a large volume of operations and large-scale transactions will be the ones to take advantage of all the benefits of such technology and find a high profitability when implementing it.

Another gap is between the modeling and validation of digital twins and their implementation or operation in the field of perishable food supply chains, since there are very few (if any) studies in which a digital twin is implemented or operated in such a context. Moreover, it is still evident that the chains most affected by food loss are those in which the areas covered by the factors in this study are weak and underdeveloped.

Future research should experiment in supply chains of perishable products, whose environments are technologically and economically suitable, to implement digital twins and go beyond modeling and validation. With this, subsequently, to find figures and quantitatively demonstrate the technical and economic advantages that digital twins can achieve. As evidenced in the study, even supply chains suffer greatly from food loss, and the next step for its mitigation is to implement Industry 4.0 tools focused on the digital twin, which has the ability to integrate and leverage them.

5. Conclusion

This study demonstrated the advantages obtained by implementing digital twins in fruit and vegetable supply chains. For this purpose, three fundamental factors were identified in this context, which allowed structuring what was exposed by several authors, pioneers in the subject. Unlike other studies on digital twins, this one focuses on the mitigation of food loss in the supply chain, which could be the first step to develop and apply this tool in the food sector. For future research, it is recommended to analyze its implementation and operation from a technical and economic approach.

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