New insights about the scientific literature of Digital Twins in Agriculture: a bibliometric study

Abdinardo Moreira Barreto de Oliveira, Federal University of Technology of Paraná, Pato Branco, Brazil, abdinardom@utfpr.edu.br

Yuri Clements Daglia Calil, Texas A&M AgriLife Extension, Corpus Christi, USA, yuri.calil@ag.tamu.edu

Juan Landivar-Bowles, Texas A&M AgriLife Extension, Corpus Christi, USA, juan.landivar@ag.tamu.edu

Luis A. Ribera, Texas A&M AgriLife Extension, College Station, USA, lribera@tamu.edu

Selected Paper prepared for presentation at the 2024 Agricultural & Applied Economics Association Annual Meeting, New Orleans, LA; July 28-30, 2024

New insights about the scientific literature of Digital Twins in Agriculture: a bibliometric study

Abstract

This article aimed to present new insights into the scientific literature on Digital Twins in agriculture, especially in the scientific mapping of their conceptual, intellectual, and social knowledge structures. Although previous literature reviews have provided some answers about the state of the art, none have conducted an in-depth assessment of the impact of the articles analyzed in this new field of scientific knowledge. A taxonomy of the main bibliometric techniques provides theoretical support. We collected metadata from the Web of Science and Scopus databases, resulting in a final collection of 89 bibliographic sources between 2018 and 2023. We employed a specific workflow for scientific mapping using the R-language's bibliometrix package. The descriptive bibliometric analysis indicated the absence of a particular bibliographic source for publishing articles on Digital Twins in agriculture, with their main production occurring in several conferences, journals, books, and reviews. The conceptual knowledge structure showed a thematic map with 13 research themes across the abstracts, divided into motor, basic, niche, and emerging/declining. The intellectual structure of knowledge showed an article co-citation network composed of two clusters and 11 main articles. Finally, the social structure of knowledge showed 22 collaboration networks between authors, 27 between institutions, and six between countries. Thus, this study provides new insights into the impact of published scientific literature on the structure of knowledge about Digital Twins in agriculture, serving as a starting point for monitoring its evolution in the coming years.

Keywords: International Development: Households, Technology, and the Environment; Agricultural Technology; Technological Adoption.

1 Introduction

The Digital Twins (DT) is a comprehensive digital and realistic representation of living and nonliving entities (assets, processes, people, places, and systems) mapped into virtual space by computer-generated models based on their features (the data). This environment allows for rapid and real-time monitoring, controlling, optimization, prediction, and improved decision-making processes to produce more favorable results and managerial learning. It can handle the challenge of seamless integration between the Internet of Things (IoT) and data analytics, providing capabilities to create new business models in rapidly evolving markets and complex economic contexts (El Saddik, 2018; Fuller et al., 2020; Haag & Anderl, 2018; Mirza, 2021; Rasheed et al., 2020; Segovia & Garcia-Alfaro, 2022).

Initially created to meet the needs of the Manufacturing Industry (Mirza, 2021), it did not take long to generate considerable interest in its application in Agriculture, given the possibilities of added value feasible for the sector (Pylianidis et al., 2021):

1. *Personalized curation of complex systems*: Digital twins adapt to local conditions in each physical twin by fusing data and learning from them;

2. *Simplification of operations*: They offer an automated pipeline of operations like data acquisition from sensors, performing simulations, creating reports, and controlling actuators, executing them continuously;

3. *Information Fusion*: Digital Twins observe physical twins from different perspectives by using multiple data sources and assessing possible outcomes of actions;

4. *Uncertainty Quantification*: They can consider the cumulative effect of the uncertainties since they observe systems from different angles;

5. *Permission Level Controls*: Digital Twins can create different levels of transparency, depending on the sensitivity of the handled data and the importance of the operations;

6. *Human-Centered Intelligence*: They can control mechanisms like human-machine interfaces for safer working environments.

In the meantime, many literature reviews provided some responses to the then state-of-the-art scientific publications on Digital Twins in Agriculture, as displayed in Table 1. However, even though these studies highlight minimal configuration, potential applications, use cases, and ethical issues about Digital Twins, they have not carried out a deeper assessment of the impact of the papers they analyzed, especially about the scientific mapping of their *conceptual* (what science talks about the central theme and trends), *intellectual* (how an author's work influences a specific scientific community) and *social* (how authors, institutions, and countries interact with each other) knowledge structures (Aria & Cuccurullo, 2017; Zupic & Čater, 2015).

Table 1: Main contributions from previous paper reviews about Digital Twins

Author	Main contribution
Onwude et al. (2020)	Digital twins as an advanced tool to diagnose and predict potential problems that increase food quality losses in the postharvest supply chains of fruits and vegetables.
Verboven et al. (2020)	It reflects how Digital Twins can be used in the agri-food sector, especially for process control, problem-solving, and operational management of the supply chain.
Defraeye et al. (2021)	Digital twins are the next logical step for postharvest technology to connect the worlds of sensing in the actual supply chain with numerical modeling in the virtual cold chain for fresh horticultural produce.
Pylianidis et al. (2021)	On a fundamental level, a Digital Twin must include monitoring, user interface, and analytic components. They are the first step towards empowering it to monitor and analyze agricultural systems and offer continuous operations.
van der Burg et al. (2021)	They offer an agenda for Responsible Research and Innovation (RRI) about Digital Twins for agri-food to anticipate and reflect on such actions' broader societal and environmental effects.
Nasirahmadi and Hensel (2022)	Digital twins paradigms can be meaningfully utilized for soil, irrigation, crops, robots and farm machinery, and postharvest food processing in the agricultural field. In this context, most studies have focused on developing digital twins by considering some of the farm sector's limited parameters.
Peladarinos et al. (2023)	The limited practical application of Digital twins technologies is obvious, even in the literature. Therefore, future research should be realized to overcome the profound lack of reference models and case studies.
Purcell and Neubauer (2023)	They identified key areas for future research, such as simulation, biological systems modeling, and business model development, which is required to allow the growth and adoption of the Digital Twin within agriculture.

This scientific mapping would make it possible to find representations of intellectual connections within a dynamically changing scientific knowledge system. Furthermore, building a map of the relationships between contemporary branches of knowledge could show us nearby areas and facilitate new connections between them. At the very least, such a map could help track how these relationships change as discoveries are made and perhaps lead to more informed management of the science and information produced (Chen, 2017) about Digital Twins.

Therefore, this article presents new insights from the scientific literature on Digital Twins based on their conceptual, intellectual, and social knowledge structures. We organized this paper into four more chapters. Chapter 2 provides an overview of the most common bibliometric techniques per unit of analysis. Chapter 3 provides the workflow for carrying out scientific mapping. Chapter 4 shows the findings related to the paper's objective. Finally, Chapter 5 presents the conclusions and final remarks.

2 A overview about bibliometric techniques

Cobo et al. (2011b) summarize in Table 2 the most bibliometric techniques used in science mapping. The development of *Bibliographic Coupling* is credited to Dr. M. M. Kessler from the Massachusetts Institute of Technology in 1963. He stated that the bibliography of technical papers is one way the authors can indicate their intellectual environment (scope and problem content). If several papers show similar bibliographies, they have an implied and meaningful relationship. So, the grouping of related documents happens through the authors' interactions with the literature, seemingly not evident at first sight. Thus, the bibliographic coupling can signal what papers should be read by whom and identify the operational life span of a given literature (Weinberg, 1974).

Table 2: A taxonomy for bibliometric techniques

Technique	Unit of analysis used	Kind of relation
Bibliographic Coupling	• Author • Document • Journal	• Common references among author's oeuvres • Common references among documents • Common references among journal's oeuvres
Co-citation	• Author • Reference • Journal	• Co-cited authors • Co-cited documents • Co-cited journals
Co-author	• Author • Country from affliation • Institution from affliation	• Co-occurrence of authors in the document's author list. • Co-occurrence of countries in the document's address list • Co-occurrence of institutions in the document's address list
Co-word	• Keyword, or term extracted from the title, abstract or document's body	• Co-occurrence of terms in a document

Seeming to be "the other side of the intellectual environment coin," the *Co-citation* was independently proposed by Small (1973) and Marshakova (1973). It is the frequency with which the later literature cites two or more items of earlier literature. Because of its dependence on the citing authors, the patterns of association between papers can change over time as the interests and intellectual patterns of the field change. So, Co-citation is a relationship that a citing author [A] establishes between cited authors [a, b]. In contrast, Bibliographic coupling is a relationship that a cited author [a] establishes between citing authors [A, B], as shown in Figure 1.

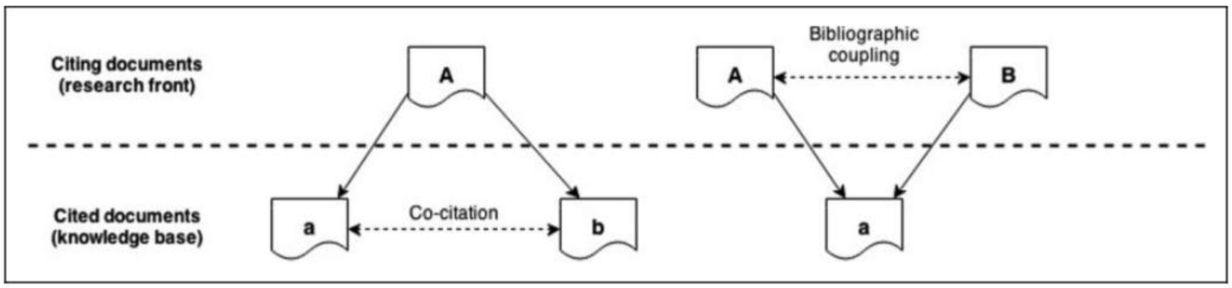

Figure 1: Difference between Co-citation and Bibliographic coupling (Zupic & Čater, 2015)

Regarding the social environment (size, composition, and authors' interaction of a specialty), De Solla Price and Beaver (1966) bring the first concept of *Co-author* technique. It aims to analyze the social life of science and the nature of collaboration and communication on the research front. They assume that the more significant part of the research front's communication occurs when the authors work together in groups.

Moreover, Stokes and Hartley (1989) highlight two kinds of authors of particular social significance: key and bridging figures. They are called *key figures* when co-authors all or most of their papers and they strongly influence a specific group. *Bridging figures* (who may also be key figures) are authors who co-authored papers in several distinct groups, forming a collaborative network.

Furthermore, because bibliographic data contain information about authors' institutional affiliations and their geographical location, the Co-author technique can examine collaboration issues on the level of institutions and countries (Zupic & Čater, 2015).

Finally, concerning the conceptual environment (cognitive structure, central themes, and trends), the *Co-word* technique is founded on the hypothesis that it is possible to identify problematic networks, poles of interest, and relationships by studying their evolution based on the content analysis of documents (Callon et al., 1983). The unit of analysis is a concept: when words frequently co-occur in documents, the ideas behind those words are closely related. Its output is a network of themes and their relations representing the conceptual space of a field, corresponding to centers of interest or research problems that are the object of substantial investments by researchers (Callon et al., 1991; Zupic & Čater, 2015).

3 Methodology

3.1 Data sources

We collected metadata from bibliographic sources on the Web of Science (WoS) - Main Collection (Clarivate Analytics) and Scopus databases, using the search expressions described in Table 3. The queries carried out focused on titles based on the following premise: if Digital Twin(s) were one of the central themes of the bibliography, it would necessarily have to appear in the work's title. Queries returned 102 papers from Scopus and 26 from WoS on April 29, 2024. We merged both queries' results, eliminating duplications and ensuring all were published by 2023. After this last filtering, the final collection had 89 bibliographic sources (88 from Scopus and 01 from WoS)[1]: 47 conference papers, 25 journal articles, 08 book chapters, 08 reviews, and 01 notes.

Table 3: Search expressions used to collect metadata from scientific databases

Database	Search expression
Scopus	TITLE (digital twin*) AND (TITLE (agri*) OR TITLE (farm*)) AND NOT (TITLE (wind*) OR TITLE (solar)) AND PUBYEAR > 2017 AND PUBYEAR < 2024 AND (LIMIT-TO (LANGUAGE, "English"))
WoS	"digital twin*" (Title) AND "agri*" OR "farm" (Title) NOT "wind*" (Title) and 2023 or 2022 or 2021 or 2020 (Publication Years) and English (Languages)

Table 4 shows the completeness of the 89 bibliographic metadata, named using the standard Clarivate Analytics WoS Field Tag codify (Aria & Cuccurullo, 2017). Therefore, it identifies the

[1] The bibliometric collection can be sent via email upon request to the authors.

degree of availability of metadata to carry out the desired bibliometric technique in Table 2.

Table 4: Completeness of bibliographic metadata obtained via `bibliometrix`

Metadata	Description	Missing counts	Missing %	Status
AB	Abstract	0	0	Excellent
C1	Affiliation	0	0	Excellent
AU	Author	0	0	Excellent
CR	Cited references	0	0	Excellent
DT	Document type	0	0	Excellent
SO	Journal	0	0	Excellent
LA	Language	0	0	Excellent
PY	Publication year	0	0	Excellent
TI	Title	0	0	Excellent
TC	Total citation	0	0	Excellent
DI	DOI	4	4.49	Good
DE	Keywords	12	13.48	Acceptable
RP	Corresponding author	31	34.83	Poor
ID	Keyword plus	31	34.83	Poor
WC	Science categories	89	100.00	Completely missing

Overall, most metadata has excellent status for executing the scientific mapping. The only concern identified was applying the Co-word technique to keywords or keyword plus, given that their status is acceptable or poor.

3.2 Analytical methods

This paper followed the science mapping workflow shown in Figure 2, employing the `bibliometrix` R-package as the primary tool, which runs in an open-source environment and ecosystem.

After the data loading and conversion stage, we performed descriptive bibliometric analysis. We presented several collection performance metrics: a) Most cited bibliographic sources, b) Most productive authors, and c) Most cited documents.

Next, we created a $Document \times Attribute$ rectangular matrix for network analysis and mapping for co-citation, co-author, and co-word techniques. We used `biblioshiny()` function to perform scientific mapping analysis because it encompasses the main functions of the `bibliometrix` R-package (Aria & Cuccurullo, 2017).

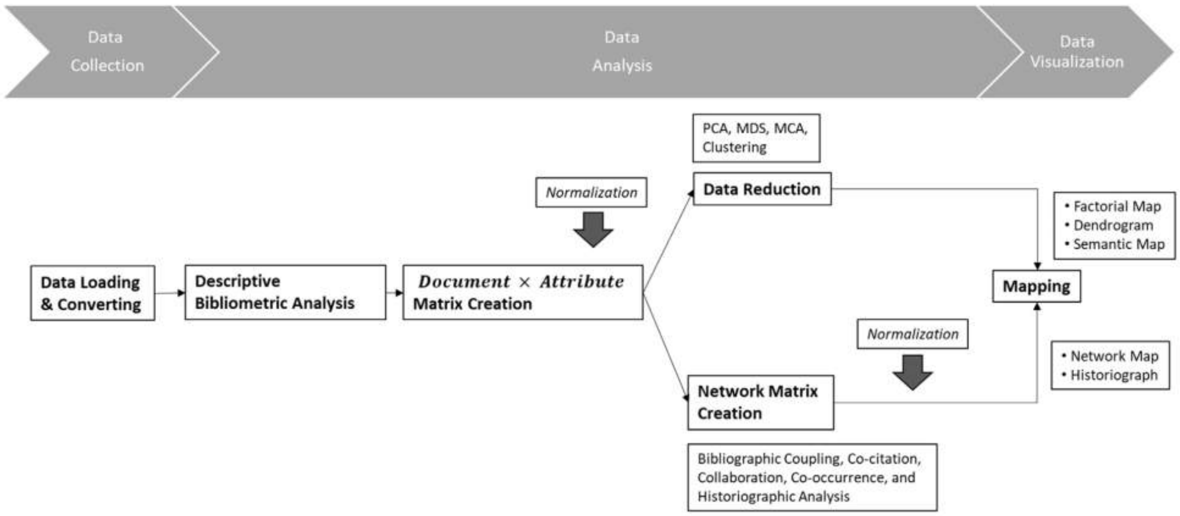

Figure 2: Science mapping workflow with `bibliometrix` (Aria & Cuccurullo, 2017)

4 Results and discussion

4.1 Collection overview

The 89 documents regarding Digital Twins in Agriculture published in 77 sources were written by 339 authors between 2018 and 2023, presenting an annual growth rate of 88.02% and 1.91 years of document average age. Moreover, each document has a mean of 4.42 co-authors and an international co-authorship rate of 16.85%. Finally, this collection has 246 author's keywords, 2,969 references, and an average of 16.09 citations per document.

Table 5 shows the most cited bibliographic sources for Digital Twins in Agriculture, ordered descending by source frequency. According to Bradford Law[2], they are located in the "core zone" of the collection (Bradford, 1976): 11 of 77 sources (14.29%) cover 23 of 89 (25.84%) cited documents, with each source having at least two mentions. Moreover, it is worth highlighting that two conferences [CEUR Workshop Proceedings and BalkanCom 2023] and two books [Lecture Notes in Computer Science and Lecture Notes in Networks and Systems] are among them.

It also shows the *h-index* (Hirsch, 2005), *g-index* (Egghe, 2006), and *m-index* (Bornmann et al.,

[2]The central assumption is that most articles on a given subject would be published in a few journals primarily devoted to that subject or its significant topic, along with specific frontier journals and more general periodicals.

Table 5: Most cited bibliographic sources for Digital Twins in Agriculture (2018 - 2023)

Rank	Source	Freq	cumFreq	*h*	*g*	*m*
1	CEUR WORKSHOP PROCEEDINGS	3	3	1	1	.33
2	2023 INTERNATIONAL BALKAN CONFERENCE ON COMMUNICATIONS AND NETWORKING, BALKANCOM 2023	2	5	1	1	.50
3	APPLIED SCIENCES (SWITZERLAND)	2	7	2	2	.50
4	COMPUTERS AND ELECTRONICS IN AGRICULTURE	2	9	1	2	.25
5	DIGITAL TWIN FOR SMART MANUFACTURING	2	11	1	1	.50
6	IEEE ACCESS	2	13	1	2	.25
7	JOURNAL OF DIGITAL LANDSCAPE ARCHITECTURE	2	15	2	2	.33
8	LECTURE NOTES IN COMPUTER SCIENCE (INCLUDING SUBSERIES LECTURE NOTES IN ARTIFICIAL INTELLIGENCE AND LECTURE NOTES IN BIOINFORMATICS)	2	17	1	2	.25
9	LECTURE NOTES IN NETWORKS AND SYSTEMS	2	19	-	-	-
10	SENSORS	2	21	2	2	.67
11	SMART AGRICULTURAL TECHNOLOGY	2	23	2	2	1.00

2008) to quantify scientific research output[3] (the higher, the better). In these criteria, **journals**, especially *Smart Agricultural Technology*, *Sensors*, and *Applied Sciences*, are increasingly prominent in publishing papers regarding Digital Twins in Agriculture.

Table 6 shows the most productive ("core") authors for Digital Twins in Agriculture. Its results are consistent with Lokta's Law[4] (Lotka, 1926): this collection has 297 (87.6%) authors with one published article and 33 (9.7%) authors with two published articles, totaling 330 (97.3%) "occasional authors."

Regarding the topic of the papers, R. Collier, Y. Kalyani, and P. Skobelev (with V. Yalovenko, A. Tabachinskiy, E. Simonova, and A. Zhilyaev each appearing three times in his papers) focused on the technical aspects of developing Digital Twins (Kalyani et al., 2022; Kalyani & Collier, 2023a, 2023b; Kalyani et al., 2023; Laryukhin et al., 2019; Skobelev, Mayorov, et al., 2021; Skobelev, Tabachinskiy, et al., 2021; Skobelev et al., 2020), while W. Purcell and T. Neubauer concentrate on the state of the art, opportunities, requirements, and challenges for creating environmentally sustainable Digital Twins, being the "core" authors with the highest number of citations (Mallinger

[3]If two articles have the same h-index, the more recent one will have a higher m-index.

[4]Inverse power law of scientific productivity: $\%Authors = 0.8987029/DocsWritten^{3.397103}$; $R^2 = 0.995$; p-value of two-sample Kolmogorov-Smirnov test between the empirical and the theoretical Lotka's Law distribution (with n=2): 0.699.

Table 6: Most productive authors for Digital Twins in Agriculture (2018 - 2023)

Authors	Year	Title	Citations
COLLIER R; KALYANI Y	2022	Integration of hypermedia-agents, microservices, and Digital Twin for smart agriculture	0
	2023	Towards a new architecture: multi-agent based cloud-fog-edge computing and Digital Twin for smart agriculture	1
	2023	Hypermedia multi-agents, semantic web, and microservices to enhance smart agriculture Digital Twin	4
	2023	Digital Twin deployment for smart agriculture in cloud-fog-edge infrastructure	3
SKOBELEV P et al.	2019	The multi-agent approach for developing a cyber-physical system for managing precise farms with Digital Twins of plants	25
	2020	Development of models and methods for creating a digital twin of plant within the cyber-physical system for precision farming management	20
	2021	Digital Twin of rice as a decision-making service for precise farming, based on environmental datasets from the fields	3
	2021	Development of Digital Twin of plant for adaptive calculation of development stage duration and forecasting crop yield in a cyber-physical system for managing precision farming	12
PURCELL W; NEUBAUER T	2022	Systemic design requirements for sustainable Digital Twins in precision livestock farming	0
	2023	Digital Twins in agriculture: challenges and opportunities for environmental sustainability	21
	2023	Digital Twins in agriculture: a state-of-the-art review	60

et al., 2022; Purcell & Neubauer, 2023; Purcell et al., 2023).

Table 7 shows the most cited documents (total and per year) for Digital Twins in Agriculture. Among them are three conceptual articles [CP], three literature reviews [LR], three prototypes [PT], and one use case [UC]. Furthermore, it is worth highlighting that, regarding Digital Twins, when comparing the data in Tables 6 and 7, the authors with the highest productivity are not necessarily the most cited authors (and vice versa). Purcell and Neubauer (2023) are the only most cited productive authors with an article listed among the most cited, even though ranked in 7th position. This differs from the findings of Abramo et al. (2014), who state that there is a moderate positive correlation between the phenomenon of being a productive top scientist and the probability of having produced highly cited articles.

Table 7: Most cited documents for Digital Twins in Agriculture (2018 - 2023)

Authors	Title	Type	Total	Per year
Verdouw et al. (2021)	Digital twins in smart farming	CP	235	58.75
Pylianidis et al. (2021)	Introducing digital twins to agriculture	LR	208	52.00
Nasirahmadi and Hensel (2022)	Toward the next generation of digitalization in agriculture based on Digital Twin paradigm	LR	90	30.00
Alves et al. (2019)	A Digital Twin for smart farming	PT	78	13.00
Ghandar et al. (2021)	A decision support system for urban agriculture using Digital Twin: a case study with aquaponics	UC	68	17.00
Angin et al. (2020)	AgriLoRa: a Digital Twin framework for smart agriculture	PT	60	12.00
Purcell and Neubauer (2023)	Digital Twins in agriculture: a state-of-the-art review	LR	60	30.00
Neethirajan and Kemp (2021)	Digital Twins in livestock farming	CP	59	14.75
Jo et al. (2018)	Smart livestock farms using Digital Twin: feasibility study	CP	53	7.57
Monteiro et al. (2018)	Towards sustainable Digital Twins for vertical farming	PT	52	7.43

4.2 Conceptual knowledge structure

This subsection shows the results of scientific mapping for the Digital Twins' conceptual knowledge structure. We built a Thematic Map[5] for Digital Twins with 13 themes shown in Figure 3.

The Thematic Map is structured on a Cartesian plane formed by *Centrality* (horizontal axis) and *Density* (vertical axis) measurements. Centrality can be understood as the measure of the importance of a theme for the development of the entire field of research analyzed. Density can be understood as a measure of the development of a theme over time in the research field in question. Based on the medians of the Centrality and Density measurements, a *Strategic Diagram* is constructed and divided into four quadrants (Callon et al., 1991; Cobo et al., 2011a):

- *Motor themes*. They cover well-developed and essential themes for structuring a field of research. They have high centrality and density.
- *Basic themes*. They are essential to the research field but are not sufficiently developed. This

[5] We built the Thematic Map focusing on the bi-grams of the abstracts. We used a dictionary of synonyms to group similar terms in writing. Each circle represents a theme: its size is proportional to the occurrences of sentences that make up the theme. We followed the standard parameterization suggested by bibliometrix.

quadrant has transversal and general themes. They have high centrality and low density.

- *Niche themes*. Their themes are well-developed but of marginal importance to the field of investigation, being considered very specialized and peripheral.

- *Emerging or declining themes*. They are peripheral and underdeveloped. Only a dynamic analysis (theme's evolution over several periods) or comparative analysis (theme's relationship with others) allows us to determine its contribution to the area.

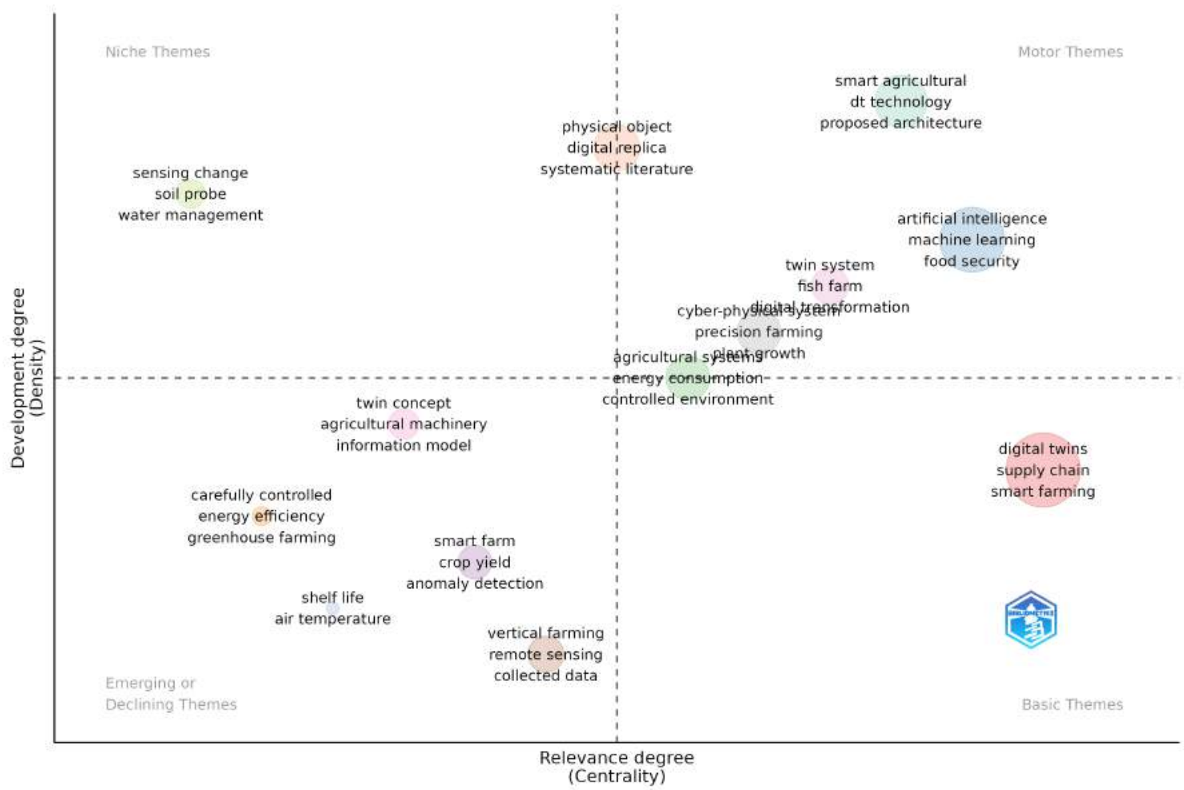

Figure 3: Thematic map for Digital Twins in Agriculture (2018 - 2023)

We identified[6] 04 motor themes, 05 emerging or declining themes, 01 basic theme, 01 niche theme, and 02 themes in a transition zone. In each theme, it is essential to analyze the meaning of the terms that compose them to understand the research problems that generate (or not) research interest. For example, the research area about Digital Twins considers how:

[6] Eleven articles in the collection were not classified into any of the 13 themes found, classified as "other" due to the heterogeneity of the research problem raised in their abstracts.

- **Motor themes** the sentences *smart agricultural/dt technology/proposed architecture* [02 papers], *artificial intelligence/machine learning/food security* [14 papers], *twin system/fish farm/digital transformation* [03 papers], *cyber-physical system/precision farming/plant growth* [05 papers];

- **Basic theme** the sentence *digital twins/supply chain/smart farming* [30 papers];

- **Niche theme** the sentence *sensing change/soil probe/water management* [03 papers];

- **Emerging or declining themes** the sentences *twin concept/agricultural machinery/information model* [02 papers], *carefully controlled/energy efficiency/greenhouse farming* [01 paper], *shelf life/air temperature* [01 paper], *smart farm/crop yield/anomaly detection* [03 papers], *vertical farming/remote sensing/collected data* [05 papers],

- **Transition themes** the sentences *agricultural systems/energy consumption/controlled environment* [04 papers], *physical object/digital replica/systematic literature* [05 papers].

Around 1/3 of the articles published on Digital Twins in Agriculture between 2018 and 2023 had their themes considered basic for the field of research [ex. Ibrahimov et al. (2023), Malik et al. (2023), Rogachev et al. (2022), Sirazetdinov et al. (2022), Tebaldi et al. (2021), van der Burg et al. (2021), Wuttke et al. (2023), and Wuyts and Huang (2023)]. In addition, 24 articles are grouped into leading themes deemed essential to the research field [ex. Kalyani et al. (2023), Kulat et al. (2023), Lan et al. (2022), and Skobelev et al. (2020)].

Finally, 13 articles are grouped into themes that seem to be emerging [ex. Chukkapalli et al. (2021), Mengi et al. (2023), and Shrivastava et al. (2023)], given their trajectory seen in the Thematic Map, with one of them tending to become a basic theme [vertical farming/remote sensing/collected data, ex. Majore and Majors (2022)] and another tending to become a theme niche [twin concept/agricultural machinery/information model, ex. Machl et al. (2019)].

4.3 Intellectual knowledge structure

This subsection shows the results of scientific mapping for the intellectual knowledge structure of Digital Twins in Agriculture. We built a Co-citation network for papers, resulting in 02 main clusters and 11 main papers shown in Figure 4, where the size node is proportional to its degree centrality measure (Koschützki et al., 2005), ranging from 0.274 to 1.00.

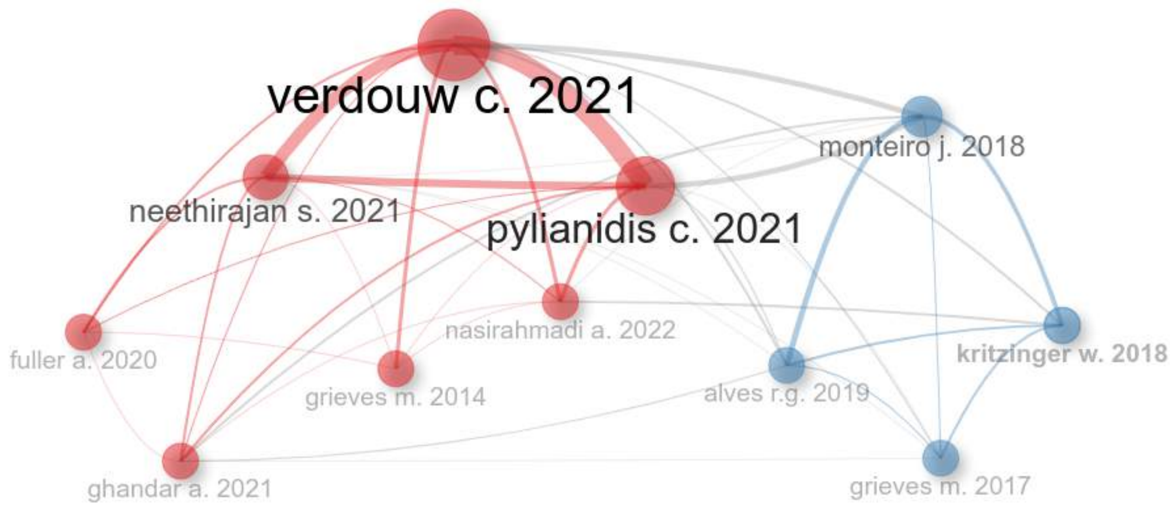

Figure 4: Co-citation network for Digital Twins in Agriculture (2018 - 2023)

In the red cluster, articles by Verdouw et al. (2021), Pylianidis et al. (2021), and Neethirajan and Kemp (2021) tend to be most co-cited since all three are conceptual papers or literature reviews on Digital Twins, Smart farming, and Livestock farming. Nasirahmadi and Hensel (2022), Fuller et al. (2020) [literature reviews], Ghandar et al. (2021) [use case], and Grieves (2014) [conceptual paper] are other references that are co-cited. Therefore, this set of articles presents the main concepts of Digital Twins and updates the scientific literature on their application in agriculture or livestock.

In the blue cluster, Monteiro et al. (2018) deals with a model for implementing Digital Twins in sustainable agriculture, co-cited mainly with Verdouw et al. (2021) and Pylianidis et al. (2021). The remaining co-cited papers bring technical examples of Digital Twins from engineering and manufacturing. Alves et al. (2019) present an initial digital environment to create a cyber-physical system so that farmers can better understand the state of their farms regarding resource and equipment utilization. Grieves and Vickers (2017) propose and discuss a Digital Twins model related to

Systems Engineering and how it can address the human interactions that lead to “normal accidents” and address obstacles and opportunities. Finally, Kritzinger et al. (2018) present a categorical literature review of the Digital Twins in manufacturing.

4.4 Social knowledge structure

This subsection shows the results of scientific mapping for the social knowledge structure of Digital Twins in Agriculture. Figure 5 shows 22 collaboration networks where the nodes are 77 authors, and the links are their co-authorships. The node’s size is proportional to the measure of its degree of centrality (Koschützki et al., 2005), ranging from 0.077 to 1.00, and the thickness of the links is proportional to the number of articles published together.

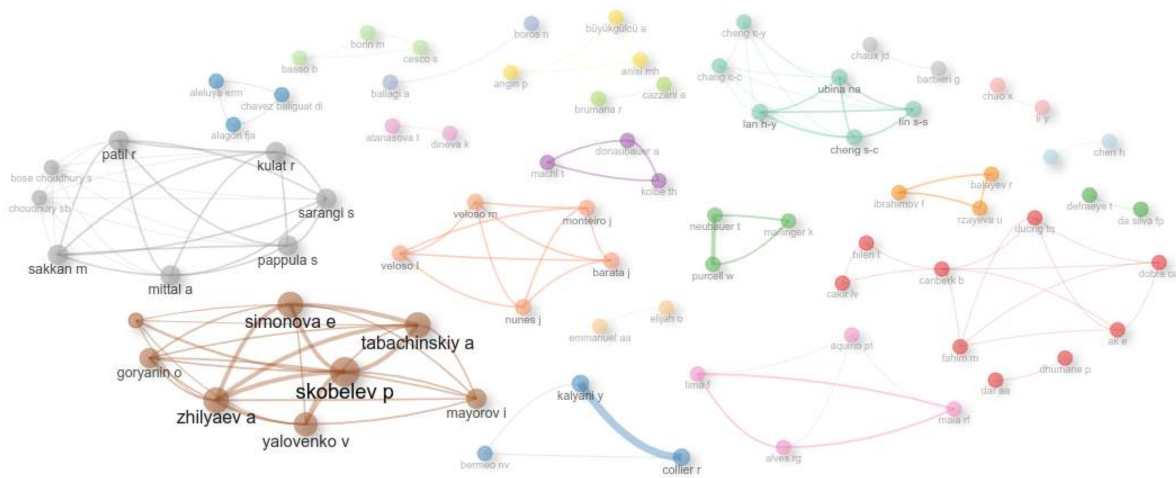

Figure 5: Collaboration network between authors for Digital Twins in Agriculture (2018 - 2023)

We found 13 authors considered *key figures* for having their degree of centrality above 0.500: Skobelev, P.; Simonova, E.; Tabachinskiy, A.; Zhilyaev, A.; Yalovenko, V.; Goryanin, O.; Mayorov, I.; Kulat, R.; Mittal, A.; Pappula, S.; Patil, R.; Sakkan, M.; Sarangi, S. However, no author was considered a *bridging figure*.

Figure 6 shows 71 institutions (nodes) in 27 collaboration networks, and the links are their partnerships. Again, the node’s size is proportional to the measure of its degree of centrality, ranging from 0.133 to 1.00, and the links’ thickness is proportional to the number of mentions of the institutions. However, we only found one institution considered a *key figure* - Wageningen University and Research - without any institution considered a *bridging figure*.

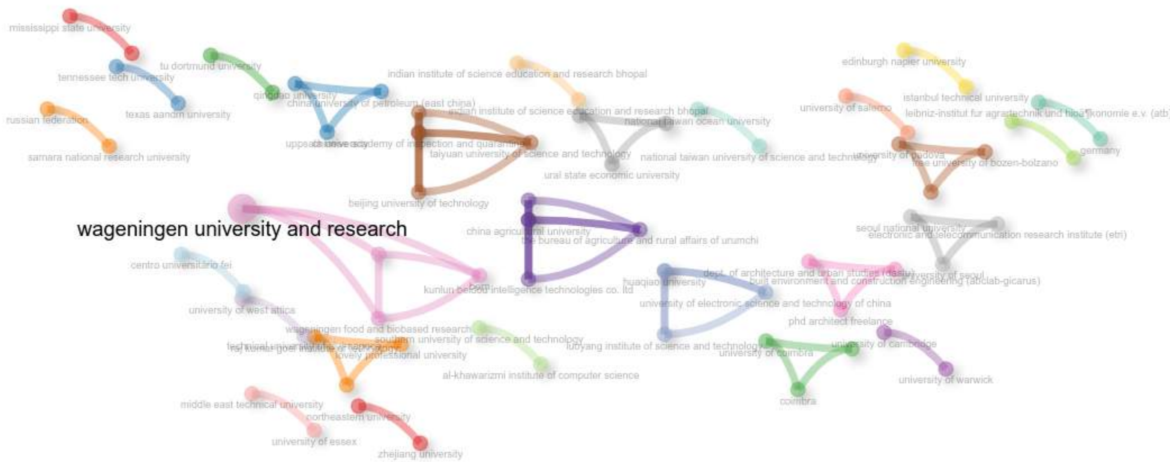

Figure 6: Collaboration network between institutions for Digital Twins in Agriculture (2018 - 2023)

At last, Figure 7 shows 21 countries (nodes) in six collaboration networks; the links are their bonding. Once again, the node's size is proportional to the measure of its degree of centrality, ranging from 0.125 to 1.00, and the links' thickness is proportional to the number of mentions of the countries. We found two countries considered *key figures* - China and the United Kingdom - without any country considered a *bridging figure*.

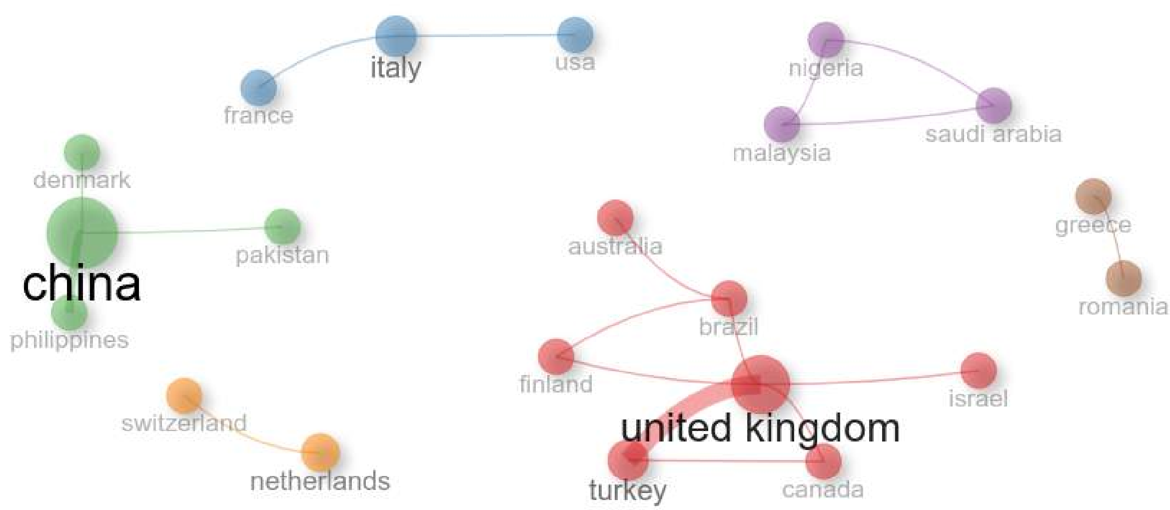

Figure 7: Collaboration network between countries for Digital Twins in Agriculture (2018 - 2023)

Thus, although there are collaboration networks between authors, institutions, and countries for studying Digital Twins in Agriculture, they seem to work independently, without any interconnection. Furthermore, it is worth highlighting that the authors' networks with key figures are linked to institutions in countries that do not participate in collaboration networks, such as Russia and India, or the only institution considered a key figure is located in a small collaboration network between countries (Netherlands and Switzerland).

5 Conclusion

The objective of this article was to present a scientific mapping of the conceptual, intellectual, and social knowledge structures of Digital Twins in agriculture based on descriptive bibliometric analysis, thematic map, co-citation, and co-authorship networks.

As for the descriptive bibliometric analysis, we identified that, between 2018 and 2023, there was no specific bibliographic source for publishing articles on Digital Twins in agriculture, with their production taking place in conferences, journals, books, and reviews, although we found the ten most cited bibliographic sources. Furthermore, we found the nine most productive authors and the ten most cited articles, even though the most productive authors are not necessarily the most cited in this research field.

Regarding the conceptual knowledge structure, our thematic map showed four motor themes, five emerging or declining themes, one basic theme, one niche theme, and two themes in a transition zone, totaling 13 research themes on Digital Twins between 2018 and 2023. We highlight the motor theme of *artificial intelligence/machine learning/food security* because of its relevance in light of climate change's effects on global agricultural production.

Concerning the structure of intellectual knowledge, we built an article co-citation network composed of two clusters and 11 main articles that deal with conceptual themes, literature review, sustainability, and technical examples about Digital Twins between 2018 and 2023.

Last but not least, we found 22 author collaboration networks, 27 collaboration networks between institutions, and six collaboration networks between countries that underlie the structure of social knowledge about Digital Twins between 2018 and 2023. We found some key figures in them, but no bridging figures could connect them. Overall, such results may be because Digital Twins is a recent topic in the agricultural sector.

Thus, this study provides new insights into the impact of the scientific literature published on the structure of knowledge about Digital Twins in agriculture. These results will be a starting point for monitoring its evolution in the coming years.

References

Abramo, G., Cicero, T., & D'Angelo, C. A. (2014). Are the authors of highly cited articles also the most productive ones? *Journal of Informetrics*, *8*(1), 89–97. https://doi.org/10.1016/j.joi.2013.10.011

Alves, R. G., Souza, G., Maia, R. F., Tran, A. L. H., Kamienski, C., Soininen, J.-P., Aquino, P. T., & Lima, F. (2019). A digital twin for smart farming. *2019 IEEE Global Humanitarian Technology Conference (GHTC)*, 1–4. https://doi.org/10.1109/GHTC46095.2019.9033075

Angin, P., Anisi, M. H., Goksel, F., Gursoy, C., & Buyukgulcu, A. (2020). AgriLoRa: A Digital Twin framework for smart agriculture. *Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications (JoWUA)*, *11*(4), 77–96. https://doi.org/10.22667/JOWUA.2020.12.31.077

Aria, M., & Cuccurullo, C. (2017). bibliometrix : An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*, *11*(4), 959–975. https://doi.org/10.1016/j.joi.2017.08.007

Bornmann, L., Mutz, R., & Daniel, H.-D. (2008). Are there better indices for evaluation purposes than the h index? A comparison of nine different variants of the h index using data from biomedicine. *Journal of the American Society for Information Science and Technology*, *59*(5), 830–837. https://doi.org/10.1002/asi.20806

Bradford, S. C. (1976). CLASSIC PAPER: Sources of Information on Specific Subjects. *Collection Management*, *1*(3-4), 95–104. https://doi.org/10.1300/J105v01n03_06

Callon, M., Courtial, J. P., & Laville, F. (1991). Co-word analysis as a tool for describing the network of interactions between basic and technological research: The case of polymer chemsitry. *Scientometrics*, *22*(1), 155–205. https://doi.org/10.1007/BF02019280

Callon, M., Courtial, J. P., Turner, W. A., & Bauin, S. (1983). From translations to problematic networks: An introduction to co-word analysis. *Social Science Information*, *22*(2), 191–235. https://doi.org/10.1177/053901883022002003

Chen, C. (2017). Science Mapping: A Systematic Review of the Literature. *Journal of Data and Information Science*, *2*(2), 1–40. https://doi.org/10.1515/jdis-2017-0006

Chukkapalli, S. S. L., Pillai, N., Mittal, S., & Joshi, A. (2021). Cyber-Physical System Security Surveillance using Knowledge Graph based Digital Twins - A Smart Farming Usecase. *2021 IEEE International Conference on Intelligence and Security Informatics (ISI)*, 1–6. https://doi.org/10.1109/ISI53945.2021.9624688

Cobo, M., López-Herrera, A., Herrera-Viedma, E., & Herrera, F. (2011a). An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to the Fuzzy Sets Theory field. *Journal of Informetrics*, *5*(1), 146–166. https://doi.org/10.1016/j.joi.2010.10.002

Cobo, M., López-Herrera, A., Herrera-Viedma, E., & Herrera, F. (2011b). Science mapping software tools: Review, analysis, and cooperative study among tools. *Journal of the American Society for Information Science and Technology*, *62*(7), 1382–1402. https://doi.org/10.1002/asi.21525

De Solla Price, D. J., & Beaver, D. (1966). Collaboration in an invisible college. *American Psychologist*, *21*(11), 1011–1018. https://doi.org/10.1037/h0024051

Defraeye, T., Shrivastava, C., Berry, T., Verboven, P., Onwude, D., Schudel, S., Bühlmann, A., Cronje, P., & Rossi, R. M. (2021). Digital twins are coming: Will we need them in supply chains of fresh horticultural produce? *Trends in Food Science & Technology*, *109*, 245–258. https://doi.org/10.1016/j.tifs.2021.01.025

Egghe, L. (2006). An improvement of the h-index: The g-index. *ISSI newsletter*, *2*(1), 8–9. https://www.issi-society.org/media/1182/newsletter05.pdf

El Saddik, A. (2018). Digital Twins: The Convergence of Multimedia Technologies. *IEEE MultiMedia*, *25*(2), 87–92. https://doi.org/10.1109/MMUL.2018.023121167

Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital Twin: Enabling Technologies, Challenges and Open Research. *IEEE Access*, *8*, 108952–108971. https://doi.org/10.1109/ACCESS.2020.2998358

Ghandar, A., Ahmed, A., Zulfiqar, S., Hua, Z., Hanai, M., & Theodoropoulos, G. (2021). A Decision Support System for Urban Agriculture Using Digital Twin: A Case Study With Aquaponics. *IEEE Access*, *9*, 35691–35708. https://doi.org/10.1109/ACCESS.2021.3061722

Grieves, M. (2014). Digital twin: manufacturing excellence through virtual factory replication. https://www.researchgate.net/publication/275211047_Digital_Twin_Manufacturing_Excellence_through_Virtual_Factory_Replication

Grieves, M., & Vickers, J. (2017). Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems. In J. Kahlen, S. Flumerfelt, & A. Alves (Eds.), *Transdisci-*

plinary perspectives on complex systems (pp. 85–113). Springer International Publishing. https://doi.org/10.1007/978-3-319-38756-7_4

Haag, S., & Anderl, R. (2018). Digital twin – Proof of concept. *Manufacturing Letters*, *15*, 64–66. https://doi.org/10.1016/j.mfglet.2018.02.006

Hirsch, J. E. (2005). An index to quantify an individual's scientific research output. *Proceedings of the National Academy of Sciences*, *102*(46), 16569–16572. https://doi.org/10.1073/pnas.0507655102

Ibrahimov, F., Rzayeva, U., & Balayev, R. (2023). Opportunities and perspectives of the digital twins' conception: the case in agriculture. *Eastern-European Journal of Enterprise Technologies*, *1*(13 (121)), 102–112. https://doi.org/10.15587/1729-4061.2023.273975

Jo, S.-K., Park, D.-H., Park, H., & Kim, S.-H. (2018). Smart Livestock Farms Using Digital Twin: Feasibility Study. *2018 International Conference on Information and Communication Technology Convergence (ICTC)*, 1461–1463. https://doi.org/10.1109/ICTC.2018.8539516

Kalyani, Y., Rahman, S., & Collier, R. W. (2022). Integration of Hypermedia-Agents, Microservices and Digital Twin for Smart Agriculture. *PoEM Workshops*, 1–12. https://ceur-ws.org/Vol-3298/paper_DTE_7846.pdf

Kalyani, Y., Bermeo, N. V., & Collier, R. (2023). Digital twin deployment for smart agriculture in Cloud-Fog-Edge infrastructure. *International Journal of Parallel, Emergent and Distributed Systems*, *38*(6), 461–476. https://doi.org/10.1080/17445760.2023.2235653

Kalyani, Y., & Collier, R. (2023a). Hypermedia Multi-Agents, Semantic Web, and Microservices to Enhance Smart Agriculture Digital Twin*. *2023 IEEE International Conference on Pervasive Computing and Communications Workshops and other Affiliated Events (PerCom Workshops)*, 170–171. https://doi.org/10.1109/PerComWorkshops56833.2023.10150413

Kalyani, Y., & Collier, R. (2023b). Towards a New Architecture: Multi-agent Based Cloud-Fog-Edge Computing and Digital Twin for Smart Agriculture. In L. Braubach, K. Jander, & C. Bădică (Eds.), *Intelligent distributed computing xv. idc 2022. studies in computational intelligence* (pp. 111–117). Springer Cham. https://doi.org/10.1007/978-3-031-29104-3_12

Koschützki, D., Lehmann, K. A., Peeters, L., Richter, S., Tenfelde-Podehl, D., & Zlotowski, O. (2005). Centrality Indices. In *Network analysis. lecture notes in computer science* (pp. 16–61). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-31955-9_3

Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital Twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine*, *51*(11), 1016–1022. https://doi.org/10.1016/j.ifacol.2018.08.474

Kulat, R., Patil, R., Bose Choudhury, S., Mittal, A., Sarangi, S., Sakkan, M., B, H., Singh, D., & Pappula, S. (2023). Monitoring and Impact Assessment of Farm Practices in Horticulture Crops with Digital Twins. *2023 IEEE Global Humanitarian Technology Conference (GHTC)*, 456–459. https://doi.org/10.1109/GHTC56179.2023.10354636

Lan, H.-Y., Ubina, N. A., Cheng, S.-C., Lin, S.-S., & Huang, C.-T. (2022). Digital Twin Architecture Evaluation for Intelligent Fish Farm Management Using Modified Analytic Hierarchy Process. *Applied Sciences*, *13*(1), 141. https://doi.org/10.3390/app13010141

Laryukhin, V., Skobelev, P., Lakhin, O., Grachev, S., Yalovenko, V., & Yalovenko, O. (2019). Towards developing a cyber-physical multi-agent system for managing precise farms with digital twins of plants. *Cybernetics and Physics*, (Volume 8, 2019, Number 4), 257–261. https://doi.org/10.35470/2226-4116-2019-8-4-257-261

Lotka, A. J. (1926). The frequency distribution of scientific productivity. *Journal of the Washington Academy of Sciences*, *16*(12), 317–323. https://www.jstor.org/stable/24529203

Machl, T., Donaubauer, A., & Kolbe, T. H. (2019). Planning agricultural core road networks based on a digital twin of the cultivated landscape. *Journal of Digital Landscape Architecture*, *4*, 316–327. https://doi.org/10.14627/537663034

Majore, G., & Majors, I. (2022). Digital twin modelling for eco-cyber-physical systems: In the case of A smart agriculture living lab. *Proceedings of PoEM Forum*, 98–112. https://ceur-ws.org/Vol-3327/paper09.pdf

Malik, P., Sneha, Garg, D., Bedi, H., Gehlot, A., & Malik, P. K. (2023). An Improved Agriculture Farming Through the Role of Digital Twin. *2023 4th International Conference on Electronics and Sustainable Communication Systems (ICESC)*, 667–671. https://doi.org/10.1109/ICESC57686.2023.10193522

Mallinger, K., Purcell, W., & Neubauer, T. (2022). Systemic design requirements for sustainable Digital Twins in precision livestock farming. *Proceedings of the 10th European Conference on Precision Livestock Farming (Vol. 29)*, 718–725. https://www.researchgate.net/publication/365034970_Systemic_design_requirements_for_sustainable_Digital_Twins_in_precision_livestock_farming

Marshakova, I. S. (1973). System of Document Connections Based on References. *Nauchno Teknnicheskaia Informatsiia*, *6*(Series 2), 3–8. https://garfield.library.upenn.edu/marshakova/marshakovanauchtechn1973.pdf

Mengi, E., Becker, C. J., Sedky, M., Yu, S.-Y., & Zohdi, T. I. (2023). A digital-twin and rapid optimization framework for optical design of indoor farming systems. *Computational Mechanics*. https://doi.org/10.1007/s00466-023-02421-9

Mirza, J. (2021). Supporting strategic management decisions. *Strategic Direction*, *37*(11), 7–9. https://doi.org/10.1108/SD-10-2021-0119

Monteiro, J., Barata, J., Veloso, M., Veloso, L., & Nunes, J. (2018). Towards Sustainable Digital Twins for Vertical Farming. *2018 Thirteenth International Conference on Digital Information Management (ICDIM)*, 234–239. https://doi.org/10.1109/ICDIM.2018.8847169

Nasirahmadi, A., & Hensel, O. (2022). Toward the Next Generation of Digitalization in Agriculture Based on Digital Twin Paradigm. *Sensors*, *22*(2), 498. https://doi.org/10.3390/s22020498

Neethirajan, S., & Kemp, B. (2021). Digital Twins in Livestock Farming. *Animals*, *11*(4), 1008. https://doi.org/10.3390/ani11041008

Onwude, D. I., Chen, G., Eke-emezie, N., Kabutey, A., Khaled, A. Y., & Sturm, B. (2020). Recent Advances in Reducing Food Losses in the Supply Chain of Fresh Agricultural Produce. *Processes*, *8*(11), 1431. https://doi.org/10.3390/pr8111431

Peladarinos, N., Piromalis, D., Cheimaras, V., Tserepas, E., Munteanu, R. A., & Papageorgas, P. (2023). Enhancing Smart Agriculture by Implementing Digital Twins: A Comprehensive Review. *Sensors*, *23*(16), 7128. https://doi.org/10.3390/s23167128

Purcell, W., & Neubauer, T. (2023). Digital Twins in Agriculture: A State-of-the-art review. *Smart Agricultural Technology*, *3*, 100094. https://doi.org/10.1016/j.atech.2022.100094

Purcell, W., Neubauer, T., & Mallinger, K. (2023). Digital Twins in agriculture: challenges and opportunities for environmental sustainability. *Current Opinion in Environmental Sustainability*, *61*, 101252. https://doi.org/10.1016/j.cosust.2022.101252

Pylianidis, C., Osinga, S., & Athanasiadis, I. N. (2021). Introducing digital twins to agriculture. *Computers and Electronics in Agriculture*, *184*, 105942. https://doi.org/10.1016/j.compag.2020.105942

Rasheed, A., San, O., & Kvamsdal, T. (2020). Digital Twin: Values, Challenges and Enablers From a Modeling Perspective. *IEEE Access*, *8*, 21980–22012. https://doi.org/10.1109/ACCESS.2020.2970143

Rogachev, A. F., Skiter, N. N., Ketko, N. V., Simonov, A. B., & Makarevich, I. V. (2022). Digital twins as a tool for systemic integration of innovative digital technologies in agriculture. *IOP Conference Series: Earth and Environmental Science*, *1069*(1), 012042. https://doi.org/10.1088/1755-1315/1069/1/012042

Segovia, M., & Garcia-Alfaro, J. (2022). Design, Modeling and Implementation of Digital Twins. *Sensors*, *22*(14), 5396. https://doi.org/10.3390/s22145396

Shrivastava, C., Schudel, S., Shoji, K., Onwude, D., da Silva, F. P., Turan, D., Paillart, M., & Defraeye, T. (2023). Digital twins for selecting the optimal ventilated strawberry packaging based on the unique hygrothermal conditions of a shipment from farm to retailer. *Postharvest Biology and Technology*, *199*, 112283. https://doi.org/10.1016/j.postharvbio.2023.112283

Sirazetdinov, R., Sabitov, R., Smirnova, G., Sabitov, S., & Eponeshnikov, A. (2022). Building a Digital Twin of agricultural production based on mathematical modeling of sustainability and development processes. *Advances in Systems Science and Applications*, *4*(22), 116–125. https://doi.org/10.25728/assa.2022.22.4.1264

Skobelev, P., Mayorov, I., Simonova, E., Goryanin, O., Zhilyaev, A., Tabachinskiy, A., & Yalovenko, V. (2020). Development of models and methods for creating a digital twin of plant within the cyber-physical system for precision farming management. *Journal of Physics: Conference Series*, *1703*(1), 012022. https://doi.org/10.1088/1742-6596/1703/1/012022

Skobelev, P., Mayorov, I., Simonova, E., Goryanin, O., Zhilyaev, A., Tabachinskiy, A., & Yalovenko, V. (2021). Development of Digital Twin of Plant for Adaptive Calculation of Development Stage Duration and Forecasting Crop Yield in a Cyber-Physical System for Managing Precision Farming. In A. G. Kravets, A. A. Bolshakov, & M. V. Shcherbakov (Eds.), *Cyber-physical systems. studies in systems, decision and control* (pp. 83–96). Springer Cham. https://doi.org/10.1007/978-3-030-67892-0_8

Skobelev, P., Tabachinskiy, A., Simonova, E., Lee, T.-R., Zhilyaev, A., & Laryukhin, V. (2021). Digital twin of rice as a decision-making service for precise farming, based on environmental datasets from the fields. *2021 International Conference on Information Technology and Nanotechnology (ITNT)*, 1–8. https://doi.org/10.1109/ITNT52450.2021.9649038

Small, H. (1973). Co-citation in the scientific literature: A new measure of the relationship between two documents. *Journal of the American Society for Information Science*, *24*(4), 265–269. https://doi.org/10.1002/asi.4630240406

Stokes, T. D., & Hartley, J. A. (1989). Coauthorship, Social Structure and Influence Within Specialties. *Social Studies of Science*, *19*(1), 101–125. https://doi.org/10.1177/030631289019001003

Tebaldi, L., Vignali, G., & Bottani, E. (2021). Digital Twin in the Agri-Food Supply Chain: A Literature Review. In A. Dolgui, A. Bernard, D. Lemoine, G. von Cieminski, & D. Romero (Eds.), *Advances in production management systems. artificial intelligence for sustainable and resilient production systems. apms 2021. ifip advances in information and communication technology* (pp. 276–283). Springer Cham. https://doi.org/10.1007/978-3-030-85910-7_29

van der Burg, S., Kloppenburg, S., Kok, E. J., & van der Voort, M. (2021). Digital twins in agri-food: Societal and ethical themes and questions for further research. *NJAS: Impact in Agricultural and Life Sciences*, *93*(1), 98–125. https://doi.org/10.1080/27685241.2021.1989269

Verboven, P., Defraeye, T., Datta, A. K., & Nicolai, B. (2020). Digital twins of food process operations: the next step for food process models? *Current Opinion in Food Science*, *35*, 79–87. https://doi.org/10.1016/j.cofs.2020.03.002

Verdouw, C., Tekinerdogan, B., Beulens, A., & Wolfert, S. (2021). Digital twins in smart farming. *Agricultural Systems*, *189*, 103046. https://doi.org/10.1016/j.agsy.2020.103046

Weinberg, B. H. (1974). Bibliographic coupling: A review. *Information Storage and Retrieval*, *10*(5-6), 189–196. https://doi.org/10.1016/0020-0271(74)90058-8

Wuttke, A., Hunker, J., Rabe, M., & Diepenbrock, J.-P. (2023). Estimating Parameters with Data Farming for Condition-Based Maintenance in a Digital Twin. *2023 Winter Simulation Conference (WSC)*, 1641–1652. https://doi.org/10.1109/WSC60868.2023.10408594

Wuyts, W., & Huang, L. (2023). A gender perspective on drones and digital twins in a transdisciplinary European smart agriculture and forestry project. In D. Bochtis, A. C. Tagarakis, & D. Kateris (Eds.), *Unmanned aerial systems in agriculture* (pp. 245–268). Elsevier. https://doi.org/10.1016/B978-0-323-91940-1.00011-6

Zupic, I., & Čater, T. (2015). Bibliometric Methods in Management and Organization. *Organizational Research Methods*, *18*(3), 429–472. https://doi.org/10.1177/1094428114562629