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DIGITAL TECHNOLOGIES SUPPORTING PREDICTIVE HEALTHCARE: REVIEW OF RESEARCH TRENDS

George Lăzăroiu
Curtin University, Australia;
Toronto Metropolitan University, Canada;
Cardiff Metropolitan University, United Kingdom
ORCID 0000-0002-3422-6310

Danuta Szpilko
Bialystok University of Technology
Poland
ORCID 0000-0002-2866-8059

Tom Gedeon
Curtin University
Australia
ORCID 0000-0001-8356-4909

Katarzyna Halicka
Bialystok University of Technology
Poland
ORCID 0000-0001-6370-8995

Agnieszka Rzepka
Lublin University of Technology
Poland
ORCID 0000-0003-4495-6066

Abstract: *This study examines research trends in digital technologies supporting predictive healthcare, with particular attention to the role of digital twins. A structured bibliometric analysis combined with qualitative thematic analysis was conducted using publications indexed in the Scopus and Web of Science databases from 2015 to 2025. The results indicate a clear shift towards integrated, data-driven healthcare solutions, in which digital twins function as central frameworks linking artificial intelligence, machine learning and Internet of Medical Things technologies. Three emerging thematic areas were identified: integrated patient data ecosystems, predictive and preventive digital twins, and digital twin–based treatment planning and patient response simulation. The findings highlight increasing interest in personalised, predictive and simulation-oriented healthcare models. At the same time, the analysis reveals a gap between technological development and routine clinical implementation. The study contributes to a clearer understanding of the evolving structure of this research field and outlines directions for future research and application in predictive healthcare.*

Keywords: *predictive healthcare, digital twin, artificial intelligence, machine learning, big clinical data, Internet of Things, Internet of Medical Things, patient monitoring, extended reality*

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INTRODUCTION

Over the past decade, healthcare systems have been undergoing an intensive process of digital transformation. One of its key directions is the development of solutions that support predictive healthcare. Increasing attention is being paid to digital technologies that enable continuous health monitoring, advanced analysis of clinical data and the forecasting of health risks and disease trajectories. In this context, wearable devices, Internet of Medical Things (IoMT) systems, artificial intelligence and healthcare digital twins have gained particular importance.

Contemporary digital healthcare solutions integrate data from multiple sources. These include physiological sensors, wearable and mobile devices, medical imaging systems and electronic health records. Such data are analysed using machine learning and deep learning methods. The aim is to support diagnosis, predict disease progression, simulate therapeutic effects and assist clinical decision-making. More recently, generative adversarial networks have been increasingly used to augment medical datasets. Such methods are particularly valuable in contexts characterised by limited availability of high-quality clinical data.

Healthcare digital twin systems represent another important development within predictive healthcare. These systems enable the modelling of patients, clinical processes or entire healthcare environments in real time. By integrating sensor data, healthcare information systems and artificial intelligence algorithms, digital twins make it possible to simulate patient health states and predict disease evolution. They also allow for the assessment of potential therapeutic interventions before their implementation. As a result, digital twins support personalised treatment, patient flow optimisation and faster clinical response, including in critical care settings such as intensive care units (Jameil & Al-Raweshidy, 2025; Rahim et al., 2024).

The expansion of predictive healthcare technologies is closely linked to issues of secure data processing and exchange. Blockchain solutions, when combined with IoMT infrastructures and digital twin systems, are increasingly analysed as tools for strengthening trust, ensuring data integrity and improving interoperability across distributed healthcare systems (Sadeghi & Mahmoudi, 2024; Addula et al., 2025). At the same time, edge computing and cloud computing architectures enable real-time data processing and scalable digital services. These technologies are particularly important for predictive applications and for health monitoring conducted outside traditional clinical environments (Jameil & Al-Raweshidy, 2024a).

The traditional reactive model is increasingly complemented by predictive, preventive and personalised approaches. Data collected from wearable devices, IoT sensors and digital twins support early detection of health disturbances, assessment of complication risks and planning of interventions tailored to individual patient characteristics. Despite the growing number of publications on predictive digital technologies in healthcare, the existing research remains thematically and methodologically fragmented. The literature covers technical, clinical, organisational and data security aspects. However, there is still a lack of a comprehensive synthesis that would organise this body of knowledge, identify dominant research streams and indicate directions for further development.

In response to this research gap, this article presents a structured review of the literature that combines bibliometric analysis with qualitative thematic exploration. The study aims to map the main research areas associated with digital technologies supporting predictive healthcare. It aims also to identify the main contributors who influence the development of this research area and to examine how its thematic focus has evolved over time. The study draws on publications indexed in the Scopus and Web of Science databases and covers the period from 2015 to 2025. Taken together, the applied approaches offer a structured and coherent picture of a research field that is expanding rapidly and spans multiple disciplinary perspectives.

The structure of the article reflects the adopted research objectives. Section 2 presents the research methodology, including the literature search strategy, publication selection criteria and applied bibliometric and qualitative methods. Section 3 reports the results of the quantitative analysis, covering publication dynamics, authorship structures, institutional and journal productivity, as well as collaboration and citation networks. Section 4 presents the results of the qualitative thematic analysis, focusing on the identification and structuring of emerging research areas in digital technologies supporting predictive healthcare. Section 5 places the findings in a broader conceptual perspective and discusses the main research directions shaping the future of the field. The article concludes with a synthesis of the key findings and a discussion of the study's limitations and directions for future research (Section 6). It also outlines implications for further research and practical application (Section 7).

METHODS

The research procedure was designed as a two-stage process: quantitative and qualitative analysis. The aim of the study was to organise and synthesise the existing body of scientific literature on predictive digital technologies in healthcare, as well as to identify the main research areas and directions for further development in this field. At the preliminary stage, three research questions were formulated: (1) Which authors, institutions, countries and journals are the most influential in research on predictive digital technologies in healthcare?; (2) Which thematic areas are most frequently addressed in publications related to predictive healthcare digital technologies?; (3) What directions for future research can be identified on the basis of the existing scientific output?

The quantitative stage was based on bibliometric analysis. The study was conducted using two international databases: Scopus and Web of Science. The identification and selection of publications followed the PRISMA guidelines, which ensured transparency and replicability of the research procedure (Figure 1). In the first step, a search strategy was defined based on the simultaneous occurrence of the keywords healthcare, predictive, digital and technology. Inclusion criteria were then specified. Publications published between 2015 and 2025 were included in the analysis. The adopted time frame made it possible to capture the evolution of research, from early and fragmented studies to the marked growth of interest in predictive healthcare digital technologies in recent years.

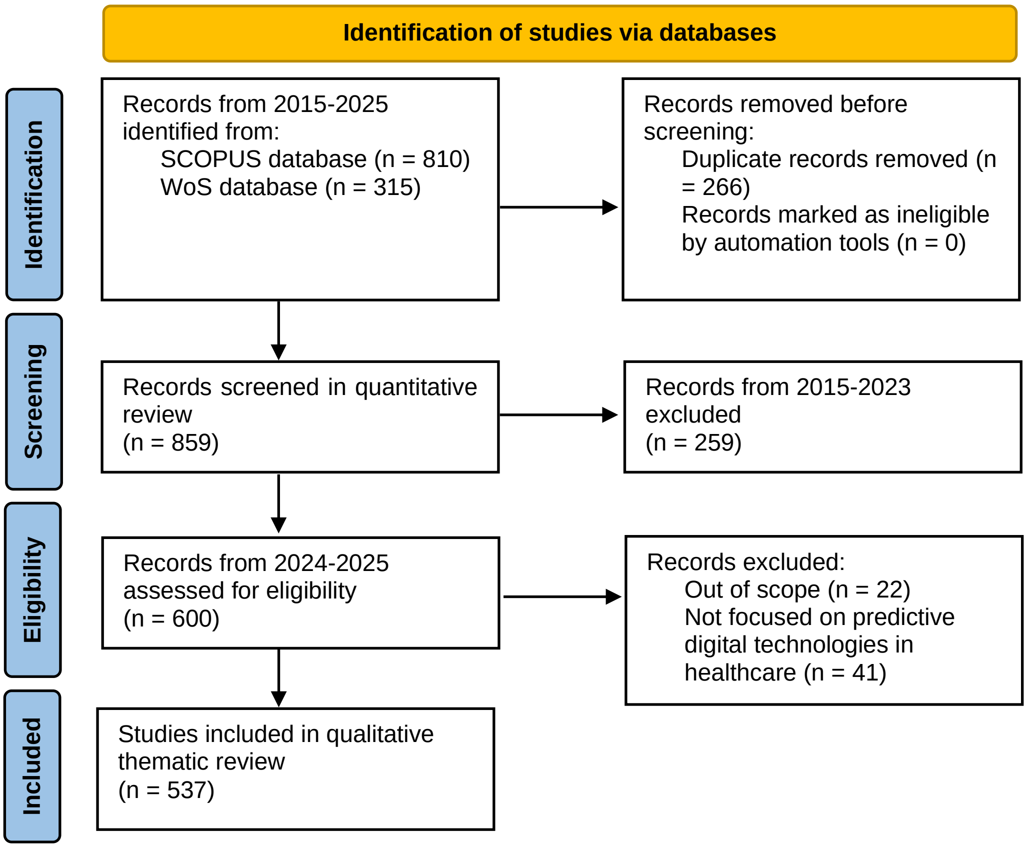

Figure 1. PRISMA flow diagram of the literature selection process.

The search strategy was designed in a stepwise manner in order to gradually narrow the set of publications and increase its thematic coherence (Table 1). In the first step, a very broad query was applied, covering the simultaneous occurrence of the terms healthcare, predictive and digital across the entire bibliographic record. This approach made it possible to identify a very large number of publications: 73,277 records in the Scopus database and 1,586 in the Web of Science database. Many of these publications were only indirectly related to the research focus.

In the second stage, the search was restricted to titles, abstracts and keywords. The application of the query TITLE-ABS-KEY (healthcare AND predictive AND digital) in Scopus and an analogous query in Web of Science significantly reduced the number of results to 1,573 publications in Scopus and 659 in Web of Science. Despite this refinement, the dataset still included studies with a diverse thematic profile, including publications in which the predictive or digital dimension played a secondary role.

The next step involved further refining the query by adding the term technology(-ies). This was intended to isolate publications in which digital technologies constitute a central element of predictive analyses in healthcare. As a result, 889 records were obtained from Scopus and 333 from Web of Science prior to the application of inclusion criteria.

Table 1. Search results.

Specification	Scopus	Web of Science
	Search 1	
Query	ALL (healthcare AND predictive AND digital)	ALL= (healthcare AND predictive AND digital)
Number of publications before inclusion criteria	73,277	1,586
	Search 2	
Query	TITLE-ABS-KEY (healthcare AND predictive AND digital)	TS = (healthcare AND predictive AND digital)
Number of publications before inclusion criteria	1,573	659
	Search 3	
Query	TITLE-ABS-KEY (healthcare AND predictive AND digital AND technolog*)	TS = (healthcare AND predictive AND digital AND technolog*)
Number of publications before inclusion criteria	889	333
Number of publications following inclusion criteria*	810	315
	Data extraction	
Removing duplicates based on titles and DOIs	859	

Note. * inclusion criteria – period: 2015-2025; document types: articles, proceedings papers, conference papers, books, book chapters, reviews, conference reviews, early access.

Subsequently, inclusion criteria were applied, covering the publication period from 2015 to 2025 and specific document types, such as journal articles, conference papers, book chapters, monographs, review articles, conference materials and early access publications. After applying these criteria, 810 publications from Scopus and 315 from Web of Science were retained for further analysis.

The final search was conducted on 30 May 2025, and the dataset was updated on 20 December 2025 as part of the review process. The update aimed to include the most recent publications and to enhance the timeliness and completeness of the analyses.

During the data extraction phase, duplicates across both databases were removed using publication titles and DOI numbers. The final research dataset consisted of 859 unique records and formed the basis for subsequent bibliometric and qualitative analyses.

Data retrieved from the Scopus and Web of Science databases were first subjected to descriptive processing using Microsoft Office Excel 25. At this stage, publication dynamics were analysed on an annual basis, and summary statistics were prepared for the most productive authors, institutions, countries and journals. Basic citation indicators were also calculated, including average citation counts and the H-index. More advanced bibliometric analyses were conducted in the RStudio environment (version 2024.12.1+563) using the Biblioshiny interface from the bibliometrix package. These tools were applied to identify the most influential publications, examine citation structures, and explore the thematic evolution and emerging research trends within the analysed field.

Network-based analyses, including co-authorship, journal co-citation and keyword co-occurrence, were performed using VOSviewer (version 1.6.20). This enabled the identification of collaboration patterns, thematic clusters and the main conceptual areas of research. The relationships between the research objectives, applied methods and analytical tools are summarised in Table 2.

Table 2. Overview of research objectives, methods and analytical tools. [Source: authors' own elaboration based on Korzeb et al., 2024; Raamkhumar & Swamy, 2024]

Objectives	Methods	Tools
Identification of publication dynamics by year and descriptive overview of the dataset	descriptive bibliometrics: annual production; most productive authors/institutions/countries/ journals; average citations; H-index	MS Office Excel 25; RStudio 2024.12.1+563 – Biblioshiny (bibliometrix) version 5.2.1
Identification of the most influential publications and citation structure	citation analysis; identification of top-cited documents; comparison of citations across Scopus and WoS	RStudio 2024.12.1+563 – Biblioshiny (bibliometrix) version 5.2.1; MS Office Excel 25
Identification of co-authorship networks (authors and countries)	co-authorship network analysis; collaboration mapping	VOSviewer version 1.6.20; RStudio 2024.12.1+563 – Biblioshiny (bibliometrix) version 5.2.1
Identification of co-citation networks (journals)	journal co-citation analysis; network visualisation and cluster detection	VOSviewer version 1.6.20; RStudio 2024.12.1+563 – Biblioshiny (bibliometrix) version 5.2.1
Identification of the conceptual structure and thematic clusters	co-occurrence analysis of author keywords; thesaurus-based keyword normalisation; network mapping; cluster identification	VOSviewer version 1.6.20; RStudio 2024.12.1+563 – Biblioshiny (bibliometrix) version 5.2.1
Identification of thematic map, thematic evolution and research trends	thematic mapping (centrality–density), thematic evolution (Sankey), trend topics analysis	RStudio 2024.12.1+563 – Biblioshiny (bibliometrix) version 5.2.1

The qualitative stage of the study was conducted after the completion of the quantitative analyses and aimed to provide a deeper interpretation of current research directions in predictive digital technologies in healthcare. Based on the selection procedure illustrated in the PRISMA flow diagram, publications published in the years 2024–2025 were selected for further analysis. This temporal focus allowed the analysis to concentrate on the most recent studies. These publications best reflect current research trends, dominant methodological approaches and emerging applications of predictive technologies in clinical practice.

In the first step, 600 publications from this period were assessed. The analysis was based primarily on abstracts, and, where further clarification was required, on full-text review. During the screening process, 63 records were excluded. These included studies falling outside the thematic scope of the research or publications not directly focused on predictive digital technologies in healthcare.

Ultimately, 537 publications were included in the qualitative thematic analysis. This stage aimed to capture the main lines of inquiry emerging in recent research. The analysis paid particular attention to the ways in which technological solutions are linked with concrete healthcare applications and to the directions in which the field appears to be evolving. Special emphasis was placed on research addressing the integration of predictive models into everyday clinical workflows, the increasing personalisation of healthcare, and the growing importance of data-driven and digital tools in medical decision-making.

RESULTS

During the analysed period from 2015 to 2025, 810 publications were identified in the Scopus database, while 317 publications were indexed in the Web of Science database. After the removal of duplicate records, a total of 859 unique papers from both databases were retained for further analysis (Figure 2).

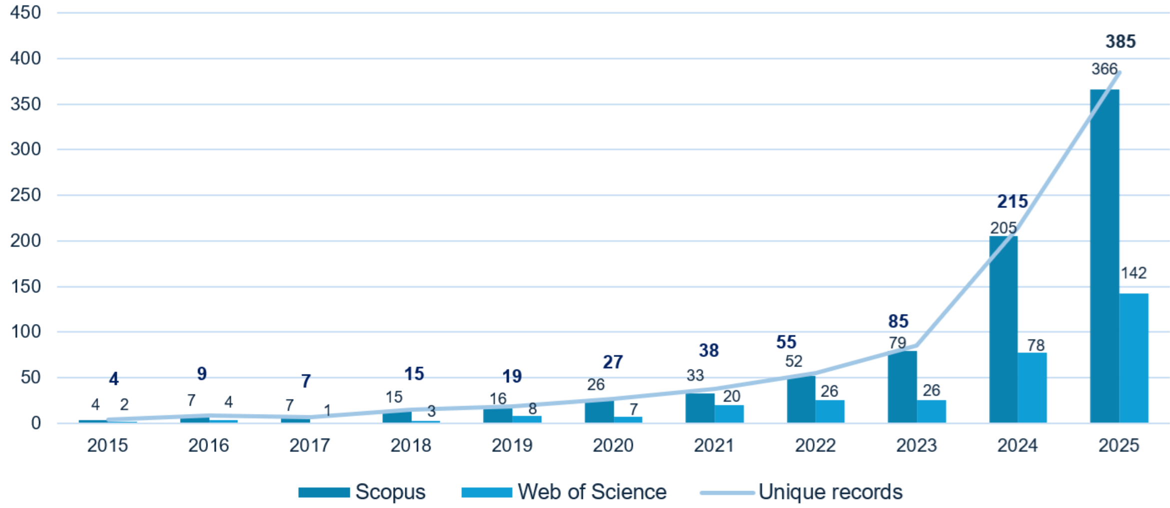

Figure 2. Number of publications in Scopus and WoS databases.

In the initial phase of the analysis, covering the years 2015–2017, research activity was limited. The annual number of unique publications did not exceed 10 items. In 2018–2019, a gradual increase was observed. The number of unique records reached 15 and 19, respectively. A more noticeable acceleration occurred in 2020. In that year, 27 unique publications were identified. The upward trend continued in 2021, when the number of records increased to 38. From 2022 onwards, the development of research became more dynamic. In 2022, 55 unique publications were recorded, followed by 85 in 2023. The strongest growth occurred in 2024 and 2025, with 215 and 385 records, respectively. The year 2025 represents the peak of the analysed period. The results indicate a steadily increasing scientific interest in digital technologies supporting predictive healthcare.

The analysis of authors' productivity in the field of digital technologies supporting predictive healthcare shows that only a small number of researchers have published at least four papers on this topic (Table 3). The highest number of publications is observed for A. K. Tyagi and J. K. Paik. Each of these authors has produced seven papers, accounting for 0.8% of the total number of analysed publications. Tyagi's work shows a low citation impact. In the Web of Science, the average number of citations is 0.6, and the H-index is 2. The publication record of J. K. Paik shows a slightly higher impact. The average number of citations is 4.2 in Scopus and 1.5 in the Web of Science. The topic-specific H-index equals 3 in Scopus and 1 in the Web of Science. B. Singh has published six papers. The average number of citations in Scopus is 2.3. The H-index for this author is 2. Both H. J. Kim and A. Khang have authored four publications each. Kim's papers received an average of 4.5 citations in Scopus and 4.7 in the Web of Science. The H-index is 2 in both databases. In the case of Khang, the average number of citations in Scopus is 6.3, with an H-index of 2.

Overall, the results indicate that even the most productive authors account for less than 1% of the total publication set. Their citation impact remains moderate. This confirms the early stage of development of the research field.

Table 3. Productivity of authors in the field of digital technologies supporting predictive healthcare.

No.	Item	Number of publication	Percent of total publications*	Average citations		H-index	
				Scopus	WoS	Scopus	WoS
1	Tyagi, A.K.	7	0.8	0.6	N/A	2	N/A
2	Paik, J.K.	7	0.8	4.2	1.5	3	1
3	Singh, B.	6	0.7	2.3	N/A	2	N/A
4	Kim, H.J.	4	0.5	4.5	4.7	2	2
5	Khang, A.	4	0.5	6.3	N/A	2	N/A

Note: * – percent of total 859 publications. N/A – data not available.
Source: authors' work.

The co-authorship map shows a clearly differentiated structure of collaboration among the authors of the analysed publications. A large and dense cluster is visible in the central part of the map. This cluster is marked in red and includes a substantial group of researchers linked by numerous co-authorship ties. On the right-hand side of the map, a smaller cluster appears in green. It is centred around P. Kartsidis and P. D. Bamidis, who act as key nodes within this group. They also connect this cluster to the main network. Links between the two clusters are present but less intensive. This indicates limited, yet meaningful, collaboration between the groups (Figure 3).

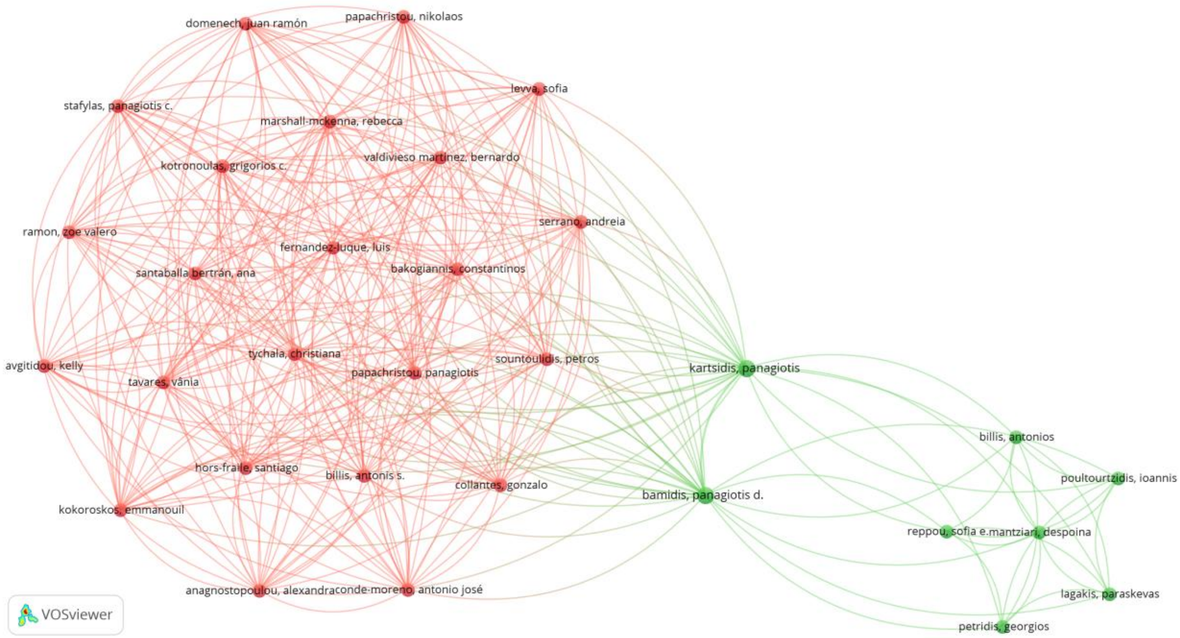

Figure 3. Author co-authorship network in research on digital technologies supporting predictive healthcare. [Source: authors' own elaboration using software VOSviewer 1.6.20]

The analysis of institutional productivity in the field of digital technologies supporting predictive healthcare indicates that even the most active research centres account for only a small share of the total publication output (Table 4). None of the institutions included in the table exceeds 1.5% of the overall number of analysed publications. The highest number of publications is recorded for Amity University (India), with 12 papers (1.4% of the total), accompanied by a moderate level of citations in both databases. A similar level of productivity is observed for SRM Institute of Science and Technology, Lovely Professional University, and Sharda University, each with 11 publications (1.3%). In the case of SRM Institute of Science and Technology, the high average number of citations in the Web of Science (38.0 citations per paper) results from a single highly cited publication, which limits broader conclusions regarding the overall impact of the institution's output. Institutions based in the United Kingdom generally show slightly lower publication volumes but a relatively higher citation impact. University College London has 10 publications (1.2%), with high average citation values in both Scopus and the Web of Science, as well as the highest H-index. University of London, despite the absence of citation data in Scopus, demonstrates visible impact in the Web of Science, with an average of 13.7 citations per paper and an H-index of 4. The remaining Indian institutions, including Symbiosis International (Deemed University), Chandigarh University, and Chitkara University, Punjab, each contributed nine publications (1.0%). Their citation impact varies from moderate to low, which further reflects the dispersed and still developing nature of research in the analysed field.

Table 4. Productivity of institutions in the field of digital technologies supporting predictive healthcare.

No.	Item	Number of publication	Percent of total publications*	Average citations		H-index	
				Scopus	WoS	Scopus	WoS
1	Amity University (India)	12	1.4	2.8	1.0	4	1
2	SRM Institute of Science and Technology (India)	11	1.3	7.7	38.0	3	1
3	Lovely Professional University (India)	11	1.3	2.1	2.3	2	2
4	Sharda University (India)	11	1.3	1.5	N/A	2	N/A
5	University College London (United Kingdom)	10	1.2	19.4	15.4	5	4
6	University of London (United Kingdom)	9	1.0	N/A	13.7	N/A	4
7	Symbiosis International (Deemed University) (India)	9	1.0	3.4	5.3	3	1
8	Chandigarh University (India)	9	1.0	5.1	15.0	3	1
9	Chitkara University, Punjab (India)	9	1.0	2.9	0	2	0

Note. * – percent of total 859 publications, N/A – data not available.

The analysis of journals publishing the largest number of articles on digital technologies supporting predictive healthcare reveals a clearly dispersed publication landscape. The most productive outlet is Lecture Notes in Networks and Systems, which published 19 papers, accounting for 2.2% of the total dataset. At the same time, this source shows very limited citation impact, with an average of fewer than one citation per article and low H-index values.

A much higher impact is observed in journals with a smaller number of publications. IEEE Access, with 14 articles, records the highest average citation rate in Scopus, exceeding 58 citations per paper, and relatively high H-index values. This indicates that studies with the strongest scientific influence tend to be published in less prolific but more visible outlets.

Journals such as Frontiers in Digital Health (14 publications) and Sensors (11 publications) combine moderate productivity with solid citation performance in both databases and comparable H-index values. This suggests their growing role as specialised publication platforms in this research area.

Conference-oriented and technical series, including Lecture Notes in Computer Science (10 publications) and Smart Innovation Systems and Technologies (12 publications), contribute a substantial number of papers, but their citation impact remains limited. This indicates that they mainly serve as dissemination channels rather than as core sources shaping the intellectual debate (Table 5).

The data indicate that despite the presence of several productive journals, scientific impact is concentrated in a small number of high-visibility outlets, while a large share of publications is dispersed across technical and conference-based sources. This pattern reflects the still evolving nature of research on digital technologies supporting predictive healthcare.

Table 5. Journals publishing the most articles on digital technologies supporting predictive healthcare.

No.	Item	Number of publication	Percent of total publications*	Average citations		H-index	
				Scopus	WoS	Scopus	WoS
1	Lecture Notes in Networks and Systems	19	2.2	0.8	0	2	0
2	Frontiers in Digital Health	14	1.6	17.1	13.7	6	5
3	IEEE Access	14	1.3	58.2	19.9	8	7
4	Smart Innovation Systems and Technologies	12	1.4	1.8	12	2	1
5	Sensors	11	1.3	10.4	8.7	5	5
6	Lecture Notes in Computer Science	10	1.2	1.3	0.5	2	1
7	Healthcare (Switzerland)	9	1.0	3.8	2.9	3	2
8	Studies in Health Technology and Informatics	7	0.8	0.4	0	1	0
9	Communications in Computer and Information Science	7	0.8	1.9	5	1	1
10	AI Powered Digital Twins for Predictive Healthcare Creating Virtual Replicas of Humans	6	0.7	0.7	N/A	1	N/A

Note. * – percent of total 859 publications, N/A – data not available.

The journal co-citation map shows that the literature in the analysed field is concentrated around 18 leading medical and interdisciplinary journals (Figure 4). One journal clearly dominates the centre of the network. This is the Journal of the American Medical Association (JAMA). It plays a key role in connecting different research streams. JAMA is frequently co-cited with the Journal of Medical Internet Research, the International Journal of Environmental Research and Public Health, and BMC Medical Education. This pattern reflects strong links between clinical research, public health, and digital health technologies. Another visible cluster consists of highly prestigious clinical journals. These include The Lancet, the New England Journal of Medicine, and the European Heart Journal. These journals are often co-cited with each other. This indicates that research on predictive healthcare technologies is firmly grounded in high-impact clinical literature. A separate but connected cluster relates to digital medicine and sensor-based research. It includes NPJ Digital Medicine, Sensors, IEEE Access, and Scientific Reports. This cluster highlights the growing role of technological and engineering approaches in predictive healthcare research. Overall, the map shows that the intellectual core of the field is shaped by the integration of clinical studies, public health research, and digital health solutions. These studies are mainly published in leading medical and interdisciplinary journals.

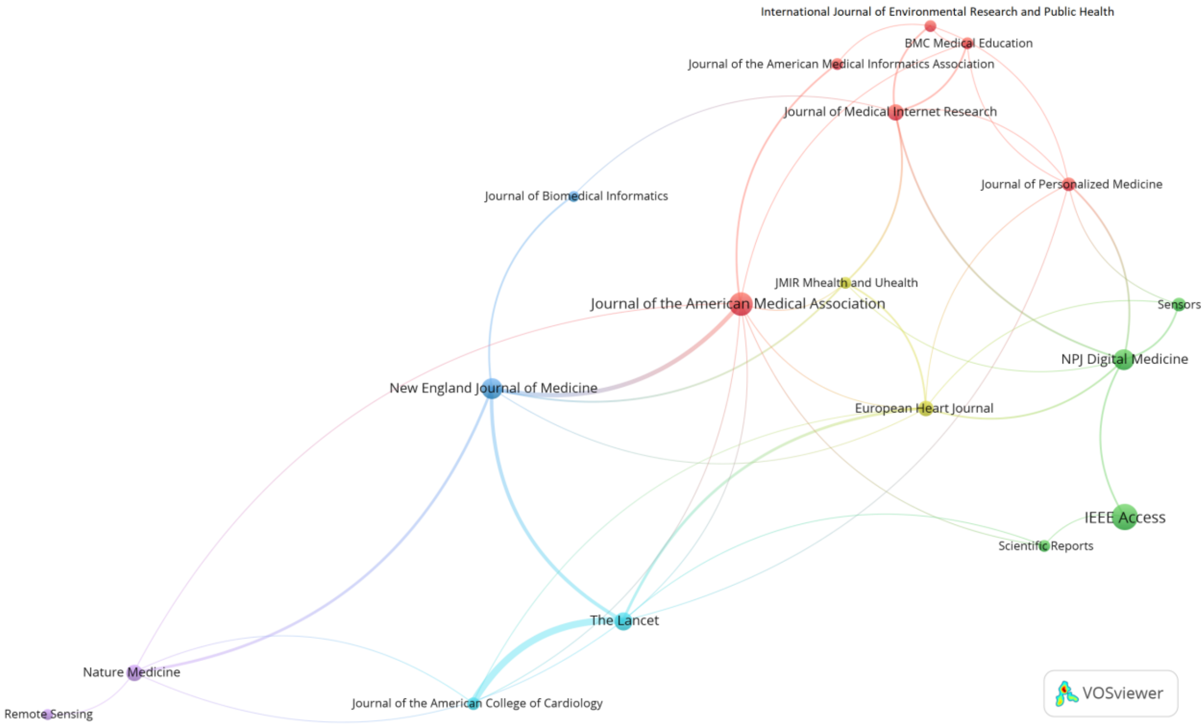

Figure 4. Journal co-citation network in research on digital technologies supporting predictive healthcare.
[Source: authors' own elaboration using software VOSviewer 1.6.20]

The country co-authorship map includes 47 countries involved in research on digital technologies supporting predictive healthcare (Figure 5). The level of international collaboration is clearly uneven. India occupies a very strong position in the network. It maintains numerous co-authorship links with other countries. Particularly strong connections are visible with the United States, the United Kingdom, and several Asian countries. The United States acts as an important connecting node. It links different collaboration clusters across regions. A clear cluster is formed by Western European countries, including the United Kingdom, Germany, France, and Italy. These countries are strongly connected with each other and with the United States. Their collaboration appears stable and well established. Another visible cluster includes countries from Asia and the Pacific region, such as China, South Korea, Singapore, and Malaysia. These countries show intensive collaboration, especially with India and the United States. Countries from Africa, South America, and the Middle East are located more peripherally. Their co-authorship links are weaker and usually limited to a small number of connections with the main research hubs.

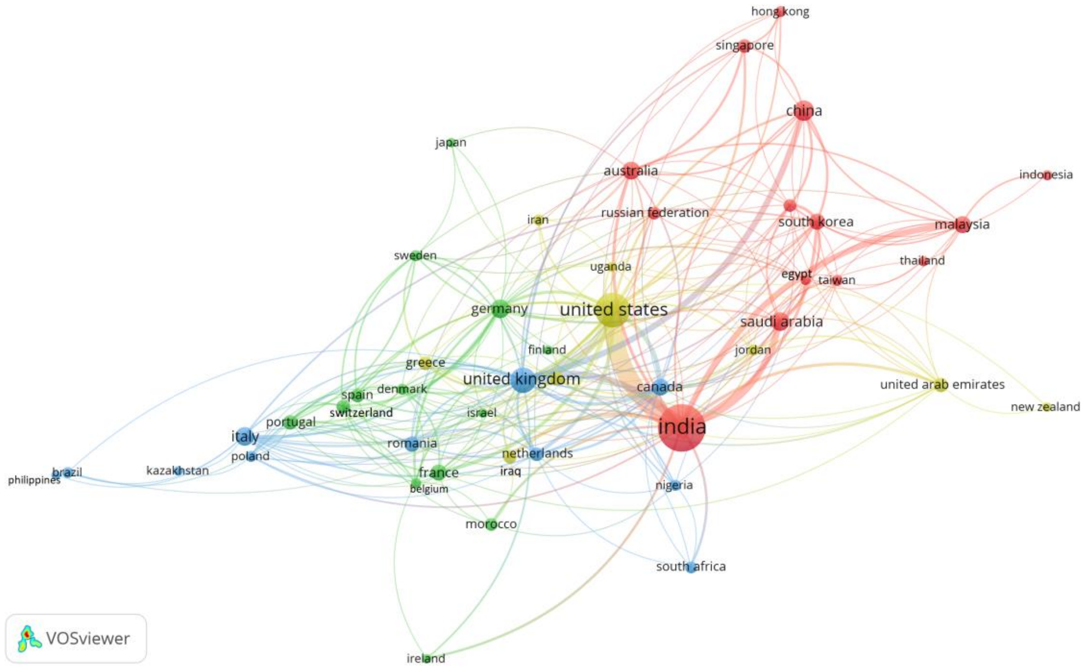

Figure 5. Country co-authorship network in research on digital technologies supporting predictive.
[Source: authors' own elaboration using software VOSviewer 1.6.20]

The geographical distribution of publications in digital technologies supporting predictive healthcare is clearly uneven. India is the most productive country, with 295 publications, accounting for 34.3% of the total output. The United States ranks second, with 134 publications (15.6%). It is followed by the United Kingdom, which produced 60 papers (7.0%). China contributes 38 publications, while Saudi Arabia and Italy each report 30 papers. Several other countries show a moderate level of research output. These include Germany (28 publications), Australia (24), Malaysia (22), and Canada (21). Together, these countries account for a smaller, yet still visible, share of the total publication volume. Citation indicators reveal a more differentiated pattern of impact. The United Kingdom records the highest average citation rates, with 26.7 citations per paper in Scopus and 23.6 in the Web of Science. Italy also demonstrates strong citation performance, with average values of 21.0 in Scopus and 18.8 in the Web of Science. The United States combines a high publication volume with a relatively strong citation impact and the highest H-index values in both databases. In contrast, some countries with high publication output, such as India and Malaysia, show lower average citation levels in Scopus, which suggests that a substantial share of their contributions is cited less frequently within the core literature of the field. In the case of China, citation impact appears more balanced across databases (Table 6).

Table 6. Countries producing the highest number of publications in digital technologies supporting predictive healthcare.

No.	Item	Number of publication	Percent of total publications*	Average citations		H-index	
				Scopus	WoS	Scopus	WoS
1	India	295	34.3	5.0	22.8	18	13
2	United States	134	15.6	18.0	20.3	25	17
3	United Kingdom	60	7.0	26.7	23.6	16	11
4	China	38	4.4	7.3	21.7	9	8
5	Saudi Arabia	30	3.5	9.0	10.1	7	6
6	Italy	30	3.5	21.0	18.8	8	6
7	Germany	28	3.3	13.8	6.2	9	7
8	Australia	24	2.8	7.6	17.7	8	7
9	Malaysia	22	2.6	13.9	4.8	7	3
10	Canada	21	2.4	11.5	3.8	6	3

Note. * – percent of total 859 publications.

The map of international co-authorships shows a clearly asymmetrical pattern of global collaboration in research on digital technologies supporting predictive healthcare (Figure 6). China and the United States act as the two main hubs of the network. They are connected by the strongest collaborative ties. China maintains particularly strong links with several Asian countries, including South Korea, Singapore, and Malaysia. Frequent cooperation is also visible with Australia. The United States occupies a central bridging position between Asia and Europe. It collaborates intensively with China, the United Kingdom, and a range of European countries.

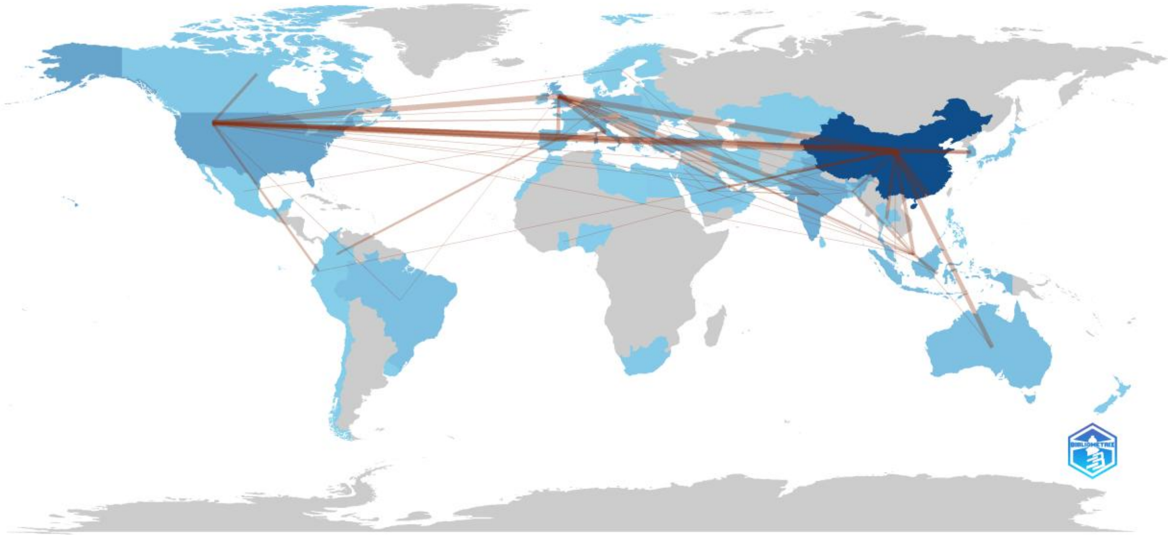

Figure 6. International collaboration network of countries in research on predictive healthcare digital technologies. [Source: authors' own elaboration using software RStudio – Biblioshiny 5.2.1]

The United Kingdom serves as the main European connector. It maintains close research ties with both China and the United States. Regular collaboration is also observed with countries such as Germany and Italy. Within Europe, collaboration is relatively dense and multi-directional. No single bilateral axis dominates the region. In contrast, countries from Africa, South America, and parts of the Middle East appear in more peripheral positions.

Their collaboration is often mediated through the main research hubs. Overall, the map indicates that the global collaboration network in this field is structured primarily around China, the United States, and the United Kingdom.

Citation data highlight a group of publications that clearly stand out in research on digital technologies supporting predictive healthcare (Table 7). The most highly cited articles are predominantly survey and review papers, indicating a strong demand for integrative and systematising studies in this field. The highest citation counts are recorded for two survey articles on digital twins. The paper by Wu et al. (2021) and the study by Mihai et al. (2022) both exceed 700 citations in Scopus and 490 citations in the Web of Science. These works serve as key reference points for research on digital twin architectures, applications, and future research directions. High citation impact is also observed for studies linking artificial intelligence and big data analytics with healthcare and sustainability outcomes. The article by Benzidia et al. (2021), which examines AI-driven green supply chain integration and hospital environmental performance, has attracted more than 500 citations in Scopus. Similarly, the study by Mamoshina et al. (2018) on blockchain and next-generation artificial intelligence technologies is frequently cited in Scopus, despite the absence of citation data in the WoS.

Several highly cited publications focus on machine learning and explainable artificial intelligence in clinical and healthcare settings. This group includes narrative and conceptual reviews, such as Peiffer-Smadja et al. (2020) and Saraswat et al. (2022), which address clinical decision support systems and the broader concept of Healthcare 5.0. Their citation levels indicate strong interest in both practical applications and ethical challenges related to AI adoption in healthcare. More recent contributions, including Giuffrè and Shung (2023) and Marques et al. (2024), concentrate on synthetic data, precision medicine, and in silico approaches. Although these studies were published recently, they already show notable citation activity, pointing to emerging research fronts within the field.

Table 7. Most cited articles in research on digital technologies supporting predictive healthcare.

No.	Authors	Article title	Journal title	Citations	
				Scopus	WoS
1	Wu Y.W., Zhang K., Zhang Y. (2021)	Digital Twin Networks: A Survey	IEEE Internet of Things Journal, 8(18)	721	523
2	Mihai S.,Yaqoob M., Hung D., Davis W., Towakel P., Raza M., Karamanoglu M., Barn B., Shetve D., Prasad R., Venkataraman H., Trestian R., Nguyen H. X. (2022)	Digital Twins: A Survey on Enabling Technologies, Challenges, Trends and Future Prospects	IEEE Communications Surveys and Tutorials, 24(4)	753	492
3	Benzidia S., Makaoui N., Bentahar O. (2021)	The impact of big data analytics and artificial intelligence on green supply chain process integration and hospital environmental performance	Technological Forecasting and Social Change, 165, 120557	547	414
4	Mamoshina P., Ojomoko L., Yanovich Y., Ostrovski A., Botezatu A., Prikhodko P., Izumchenko E., Aliper A., Romantsov K., Zhebrak A., Ogu I. O., Zhavoronkov A.	Converging blockchain and next-generation artificial intelligence technologies to decentralize and accelerate biomedical research and healthcare	Oncotarget, 9(5)	414	N/A

	(2018)				
5	Peiffer-Smadja N., Rawson T.M., Ahmad R., Buchard A., Pantelis G., Lescure F.-X., Birgand G., Holmes A.H. (2020)	Machine learning for clinical decision support in infectious diseases: a narrative review of current applications	Clinical Microbiology and Infection, 26(5)	413	N/A
6	Saraswat D., Bhattacharya P., Verma A., Prasad V. K., Tanwar S., Sharma G., Bokoro P. N., Sharma R. (2022)	Explainable AI for Healthcare 5.0: Opportunities and Challenges	IEEE Access, 10	377	169
7	Giuffrè, M., Shung, D.L. (2023)	Harnessing the power of synthetic data in healthcare: innovation, application, and privacy	Npj Digital Medicine, 6(1), 186	222	179
8	Marques L., Costa B., Pereira M., Silva A., Santos J., Saldanha L., Silva I., Magalhães P., Schmidt S., Vale N. (2024)	Advancing Precision Medicine: A Review of Innovative In Silico Approaches for Drug Development, Clinical Pharmacology and Personalized Healthcare	Pharmaceutics, 16(3), 332	188	141
9	Rehman A., Abbas S., Khan M. A., Ghazal T. M., Adnan K.M., Mosavi A. (2022)	A secure healthcare 5.0 system based on blockchain technology entangled with federated learning technique	Computers in Biology and Medicine, 150, 106019	181	N/A
10	Fitzpatrick P.J. (2023)	Improving health literacy using the power of digital communications to achieve better health outcomes for patients and practitioners	Frontiers in Digital Health, 5, 1264780	177	N/A

Note. * – percent of total 859 publications, N/A – data not available.

Author keywords were analysed as part of the bibliometric study of research on digital technologies supporting predictive healthcare. The co-occurrence mapping was carried out using VOSviewer. Before the analysis, a dedicated thesaurus file was prepared. It was used to unify terminology and correct inconsistencies in keyword spelling and meaning. Closely related terms were merged. This step improved the overall coherence of the dataset. At the initial stage, 87 author keywords met the minimum threshold of at least five occurrences. General or redundant terms were then reviewed and removed. Expressions with similar meanings were harmonised. The aim was to focus on more specific and analytically relevant concepts. After the cleaning process, 64 distinct author keywords remained. These keywords were used to construct the co-occurrence map. The map illustrates the main thematic areas of the field and the relationships between them (Figure 7).

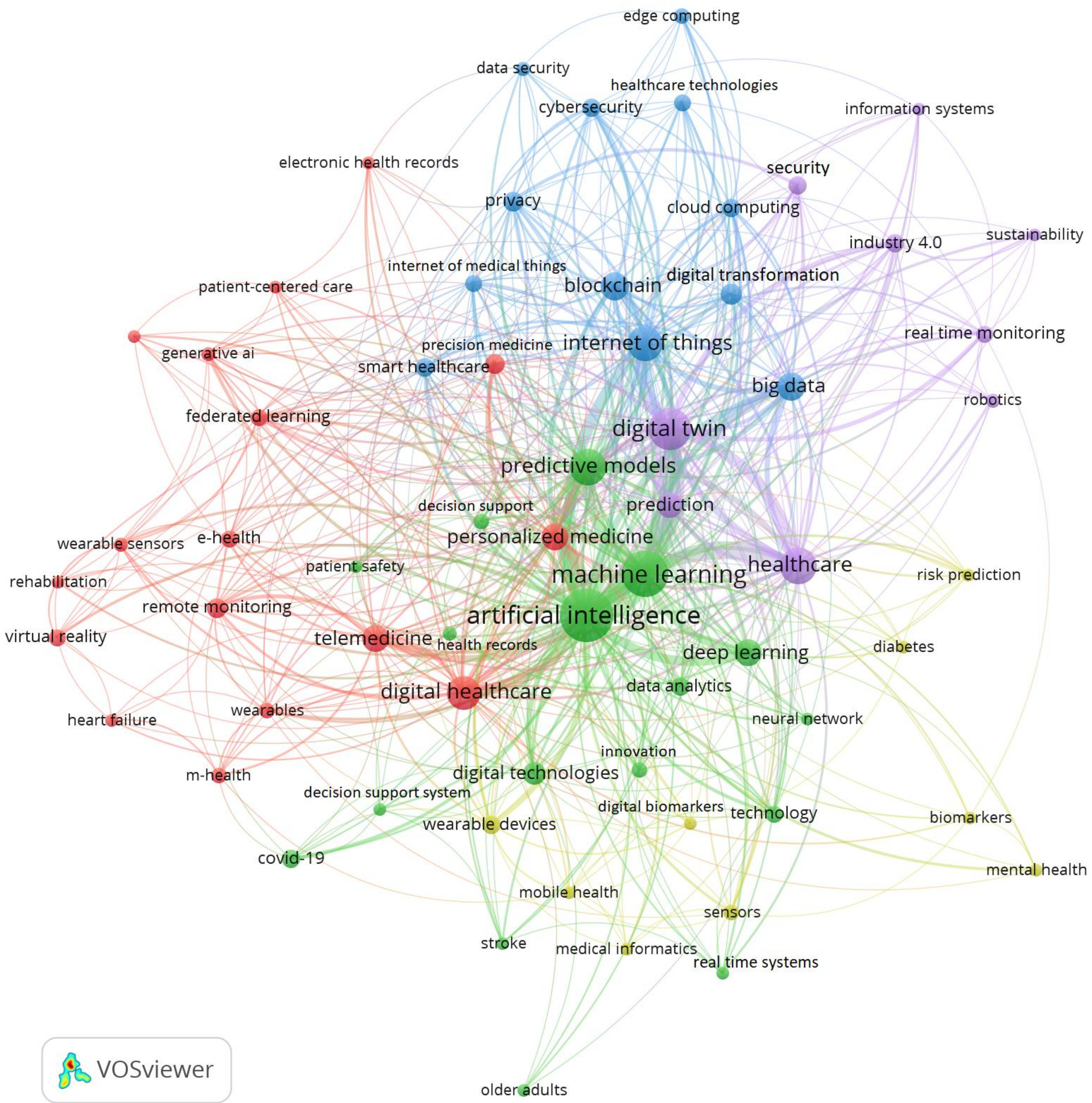

Figure 7. Co-occurrence network of author keywords in research on predictive healthcare digital technologies. [Source: authors' own elaboration using software VOSviewer 1.6.20]

A co-occurrence analysis of author keywords was conducted to identify the main research themes in studies on digital technologies supporting predictive healthcare. Only keywords that appeared in at least five publications were included in the analysis. This threshold helped to focus on the most established and recurrent topics in the literature. The analysis resulted in the identification of five major thematic clusters, which are summarised in Table 8. Each cluster represents a distinct but interrelated research sub-area within the field.

Table 8. Main research sub-areas in digital technologies supporting predictive healthcare.

No.	Research sub-areas	Keywords
1	Digital and personalised healthcare (red)	digital healthcare (65), telemedicine (36), personalized medicine (35), remote monitoring (17), precision medicine (16), federated learning (12), e-health (10), virtual reality (10), m-health (8), wearables (8), generative ai (7), wearable sensors (7), electronic health records (5), heart failure (5), oncology (5), patient-centered care (5), rehabilitation (5)
2	Artificial intelligence and predictive models in healthcare (green)	artificial intelligence (200), machine learning (140), predictive models (73), deep learning (33), digital technologies (22), COVID-19 (13), data analytics (13), technology (12), innovation (9), decision support (8), health records (7), decision support system (6), patient safety (6), neural network (5), older adults (5), real-time systems (5), stroke (5)
3	Digital infrastructure and data security in healthcare (blue)	internet of things (68), big data (39), blockchain (38), digital transformation (18), privacy (17), cloud computing (14), cybersecurity (14), smart healthcare (14), healthcare technologies (12), internet of medical things (12), edge computing (8), data security (7)
4	Wearable devices and digital biomarkers (yellow)	wearable devices (14), sensors (8), biomarkers (6), mobile health (6), diabetes (5), digital biomarkers (5), medical informatics (5), mental health (5), risk prediction (5)
5	Digital twin and predictive systems in healthcare (violet)	digital twin (111), healthcare (79), prediction (31), industry 4.0 (13), security (13), real-time monitoring (12), robotics (7), information systems (6), sustainability (5)

The first cluster, "Digital and personalised healthcare", brings together studies that examine the ongoing digital transformation of healthcare systems. This transformation is discussed both from the perspective of patients and from the viewpoint of how care is organised and delivered. Much of the literature concentrates on digital healthcare and telemedicine as emerging modes of service provision. These concepts are used to describe new forms of medical care, including remote and hybrid models that extend beyond traditional clinical settings. Empirical findings suggest that such solutions improve access to healthcare services, support more continuous monitoring of patients' health status and encourage greater patient involvement in the treatment process (Chen et al., 2025b; Wellmann et al., 2024). A well-defined line of research within this cluster relates to personalised and precision medicine. In this context, digital technologies are applied to adapt therapeutic interventions to individual patient characteristics. The analysed studies emphasise the importance of clinical data, patient-generated information and longitudinal health records in the design of personalised care pathways. These approaches are particularly visible in areas such as oncology, heart failure and the management of chronic diseases, where individual variability plays a critical role in treatment outcomes (Samathoti et al., 2025; Wattanachayakul et al., 2024). The cluster also encompasses work on remote monitoring solutions that enable the continuous observation of health parameters outside medical institutions. The literature indicates that these approaches allow for earlier identification of health deterioration and provide support for rehabilitation processes. At the same time, they reinforce patient-centred models of care, which are especially relevant in long-term treatment and during the post-hospitalisation phase (Wellmann et al., 2024; Ardelean et al., 2024). In addition, several studies focus on the use of wearable devices, wearable sensors and virtual reality technologies as tools that support therapy, rehabilitation and patient education. These technologies are discussed mainly in relation to improving patient experience and further advancing the personalisation of healthcare interventions (Smokovski et al., 2024; Baron & Haick, 2024).

The cluster "Artificial intelligence and predictive models in healthcare" encompasses research focused on the use of artificial intelligence, machine learning, and predictive models in the analysis of health data and in supporting clinical decision making. A central role is played by machine learning and deep learning algorithms, which are applied to disease trajectory prediction, risk identification, and early detection of health threatening conditions (Chen et al., 2025b; Pinto et al., 2025). An important research stream concerns the development of predictive models based on clinical data, electronic health records, and real time generated data. These models are used, among others, for predicting exacerbations of chronic diseases, detecting sepsis, forecasting stroke events, and assessing the risk of rehospitalisation (Pinto et al., 2025; Boussi Rahmouni et al., 2025). The cluster also strongly represents studies on decision support and decision support systems that integrate artificial intelligence algorithms into clinical practice. These studies emphasise the role of automated data analysis in improving patient safety, reducing the workload of medical staff, and supporting therapeutic decisions in time critical environments such as intensive care units (Boussi Rahmouni et al., 2025; Shankar et al., 2025). A clearly visible research theme relates to the application of artificial intelligence in the care of older adults and patients with chronic conditions. The findings indicate that predictive algorithms can support early infection detection, monitoring of health deterioration, and the personalisation of therapeutic interventions in older populations (Tana et al., 2025; Pinto et al., 2025). The COVID-19 pandemic provided an additional developmental impulse for this cluster. Predictive models and analytical tools were extensively used to forecast resource demand, analyse the spread of infection, and optimise decision making processes within healthcare systems (Nair et al., 2025). This cluster reflects a shift in research towards data driven healthcare, in which artificial intelligence plays a key analytical role.

The "Digital infrastructure and data security in healthcare" cluster covers work that examines the technical underpinnings of contemporary digital health systems. It describes, in a fairly practical way, how health data are acquired, transmitted, processed and protected as care becomes increasingly data-intensive and interconnected. A recurring theme is the role of Internet of Things and Internet of Medical Things solutions. These technologies enable continuous data collection and support the integration of information produced by multiple medical devices. In this way, data that were previously fragmented can be brought together and used within more coordinated clinical workflows. The literature underlines that this level of connectivity is a fundamental condition for the development of smart healthcare solutions and for systems that rely on real-time data processing (Sadeghi & Mahmoudi, 2024; Yigit et al., 2024). Alongside connectivity, the cluster gives substantial attention to data volume and computing capacity. Studies on big data and cloud computing show how cloud platforms enable healthcare organisations to scale digital services and combine sensor-derived data with electronic health records. This integration is presented as a key condition for analysing large datasets and delivering more advanced digital health solutions (Bellavista & Di Modica, 2024). The expansion of distributed digital infrastructures is accompanied by a new set of challenges. A key concern relates to the protection of sensitive health data. The literature increasingly points to risks associated with privacy breaches, cyberattacks and the loss of data integrity. As a result, a substantial body of research addresses security-related issues, particularly in settings characterised by a rapidly growing number of interconnected devices (Nankya et al., 2024; Otoom, 2025). Within this line of research, blockchain is discussed as a promising solution. It is most often presented as a tool that can strengthen trust and transparency in data management. The literature also highlights its potential to reduce the risk of data breaches and to improve interoperability between healthcare systems that are otherwise poorly integrated (Addula et al., 2025; Adeniyi et al., 2024). Edge computing appears in the same line of argument as a complementary solution. By relocating part of the processing closer to the data source, it can reduce latency and lessen reliance on cloud resources, which is particularly relevant for real-time monitoring scenarios (Jameil & Al-Raweshidy, 2024b).

The “Wearable devices and digital biomarkers” cluster comprises studies examining the use of wearable technologies and digital biomarkers in health monitoring. This body of research concentrates on technological solutions that allow for the continuous and non-invasive acquisition of physiological data. A key feature of these approaches is that data collection takes place in everyday settings, beyond conventional clinical environments. Central to this cluster are wearable devices and sensors, which provide real-time information on an individual’s health status. A key line of inquiry within this body of work concerns digital biomarkers. These are defined as measurable indicators of health that are derived directly from data generated by digital technologies. These biomarkers are increasingly used to detect early changes in health condition and to monitor disease progression over time (Smokovski et al., 2024; Wasilewski et al., 2024). The literature consistently highlights their role in supporting a gradual shift from reactive healthcare towards more predictive and personalised models of care. Mobile health technologies emerge in the literature as a particularly important area of application within this cluster. This is most clearly reflected in studies focusing on diabetes and cardiovascular diseases. In these settings, information collected through wearable sensors is integrated with predictive modelling techniques. This combination supports clinical risk evaluation and enhances anticipatory decision-making. In particular, it allows clinicians to identify early warning signals, such as impending glycaemic events or the onset of clinical deterioration in patients with chronic diseases (Ying et al., 2025; Wattanachayakul et al., 2024). These approaches contribute to earlier clinical responses and improved disease management. Mental health applications are also clearly represented in this cluster. Analyses in this area often focus on physiological parameters such as sleep patterns and heart rate variability. These measures are used to derive digital indicators of stress and psychological burden (Rana et al., 2025; Pataca et al., 2025).

The “Digital twin and predictive systems in healthcare” cluster focuses on digital twins and predictive systems in healthcare. It covers models that represent a patient, a clinical process, or a hospital environment. These models are fed with sensor and information system data. They often operate in real time (Jameil & Al-Raweshidy, 2025; Rahim et al., 2024). The literature highlights continuous monitoring and early anomaly detection. It also stresses the integration of cloud, edge solutions, and AI. The aim is to shorten response time and improve predictive performance (Jameil & Al-Raweshidy, 2024b). Emergency management is an important strand. Digital twins are linked to operational decision-making and system load forecasting. Issues related to system resilience and the efficient flow of information emerge as important themes in this body of research (Zheng et al., 2025). Many studies also explicitly refer to the concepts of Industry 4.0 (Lăzăroiu et al., 2022a,b; Andronie et al., 2023a,b) and the Internet of Things, which frame digital twins as integral components of broader processes of digital transformation in healthcare systems. In this view, they support data integration and predictive decisions (Bongomin et al., 2025; Narigina et al., 2024). Security is also central. It concerns privacy, data integrity, and cyber risks. The literature addresses a range of security-related mechanisms, including encryption methods, authentication procedures and approaches to risk auditing. In this context, blockchain is frequently analysed as a potential means of enhancing trust and enabling secure data exchange across healthcare systems (Addula et al., 2025; Nankya et al., 2024; Otoom, 2025; Sadeghi & Mahmoudi, 2024). At the same time, applied studies extend these technological considerations to clinical domains, with particular attention given to areas such as cardiology and oncology. Authors point to personalised simulation and risk prediction. At the same time, they note the need for stronger validation and implementation readiness (Stefaniga et al., 2024; Thangaraj et al., 2024).

As part of the conducted analyses, a thematic map was also developed (Figure 8). Its purpose was to capture the structure and directions of research on digital technologies supporting predictive healthcare.

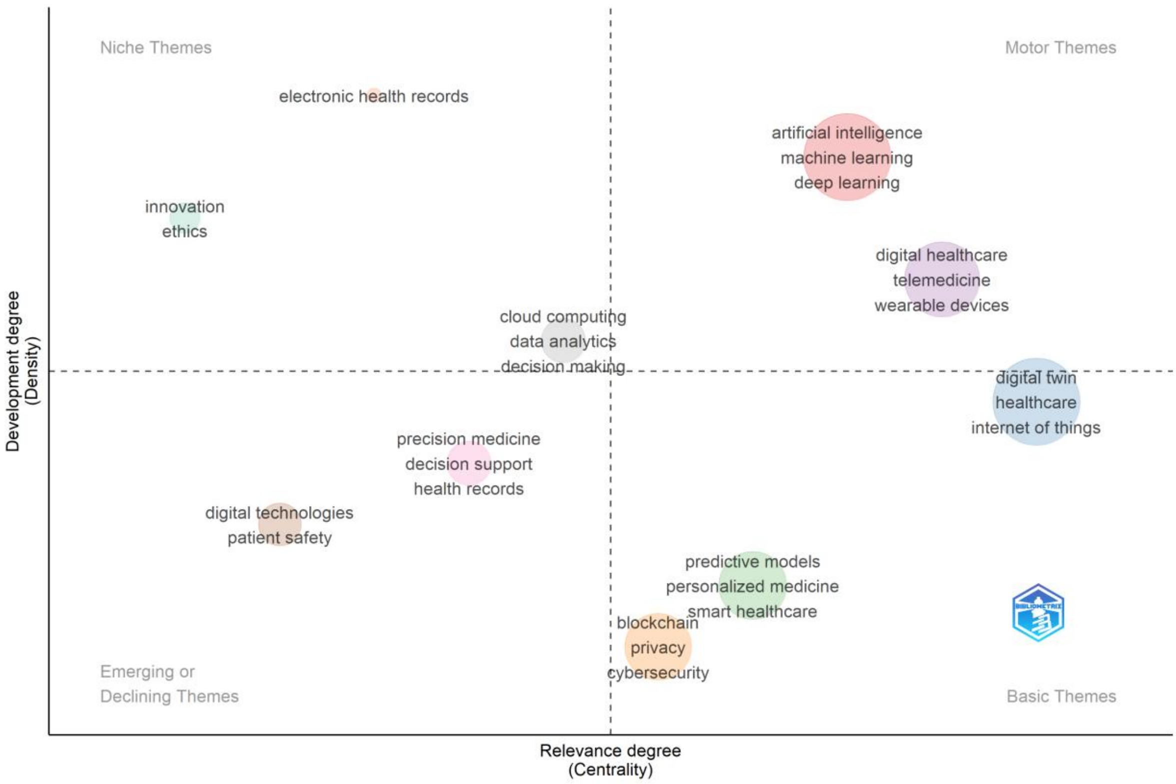

Figure 8. Thematic map of research on digital technologies supporting predictive healthcare.
[Source: authors' own elaboration using software RStudio – Biblioshiny 5.2.1]

The map makes it possible to identify both central research areas and more specialised themes, while taking into account their level of development and their connections with other topics. A central position on the map is occupied by themes related to artificial intelligence, including machine learning and deep learning (high centrality and high density). Their location confirms that AI-based approaches currently form the core of research on predictive healthcare. These themes are strongly integrated with other research streams and are intensively developed. Close to this core are themes such as digital healthcare, telemedicine, and wearable devices (high centrality and moderate density). Their placement indicates that digital care models and remote monitoring technologies have become a stable element of the dominant research discourse. An important position on the map is also held by topics related to data security and digital infrastructure. Themes such as blockchain, privacy, and cybersecurity are located among the basic themes (high centrality with moderate density). This suggests that they are strongly connected with other research areas but are still undergoing systematic development. Blockchain appears mainly in the context of data integrity protection, trust in predictive systems, and the secure exchange of medical information between healthcare stakeholders.

Themes such as predictive models and personalised medicine play a supporting role (high centrality, moderate density). They provide a conceptual foundation for the application of AI and secure data-processing systems, although their internal consolidation is still in progress. At the margins of the map, more specialised topics can be observed, including electronic health records, ethics, and innovation (lower centrality with relatively higher density). These themes often appear in regulatory, organisational, and ethical contexts, particularly in relation to data security and the responsible use of blockchain and AI technologies.

The previous static analyses are complemented by a thematic evolution map, which makes it possible to trace how the main research topics have changed over time. The Sankey diagram shown in Figure 9 illustrates both continuity and thematic shifts in research on digital technologies supporting predictive healthcare.

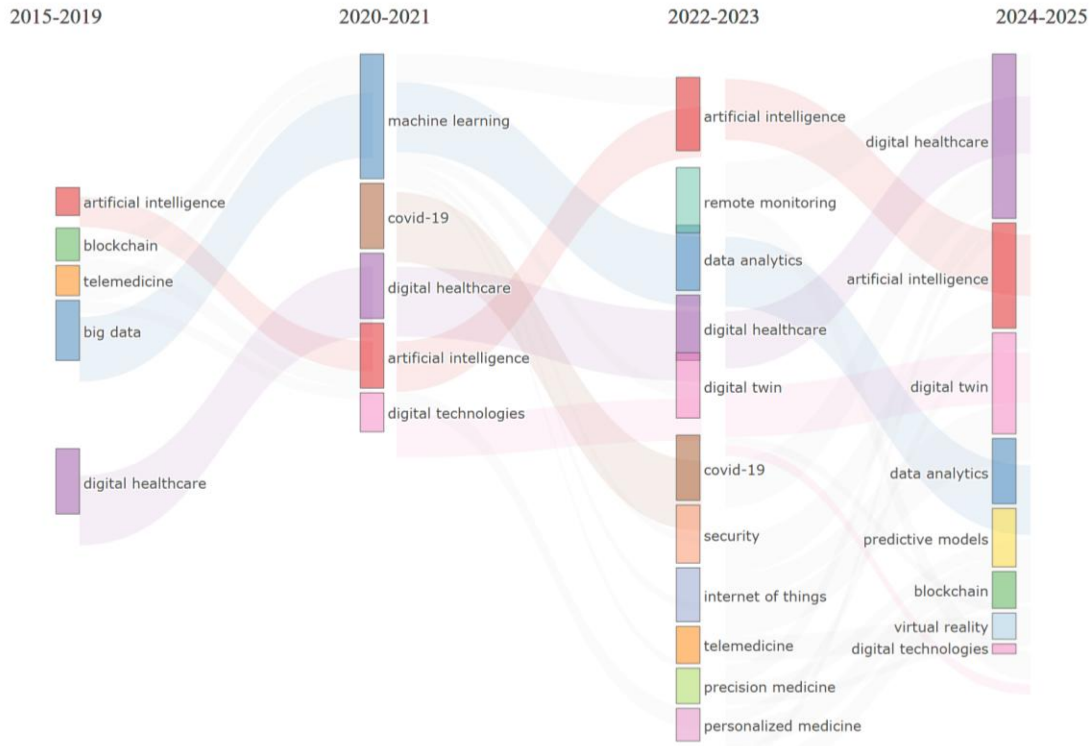

Figure 9. Thematic evolution of research on digital technologies supporting predictive healthcare.
[Source: authors' own elaboration using software RStudio – Biblioshiny 5.2.1]

In the first period (2015–2019), the thematic scope was relatively narrow. Research focused mainly on broad concepts such as artificial intelligence, blockchain, telemedicine, and big data. These terms functioned more as general technological frames than as components of mature analytical models. The early presence of digital healthcare already signalled the later development of this research stream. During 2020–2021, the thematic structure became more differentiated. Machine learning gained visibility, while COVID-19 emerged as an important, though temporary, topic. At the same time, research on digital healthcare and artificial intelligence expanded, indicating a shift towards more advanced analytical methods and clinical applications.

The period 2022–2023 was marked by further deepening and specialisation. Alongside artificial intelligence and digital healthcare, topics such as data analytics, remote monitoring, and digital twin became more prominent. At the same time, themes related to security and the internet of things developed more strongly, reflecting the growing importance of digital infrastructure and data protection in predictive systems. In the most recent period (2024–2025), the focus moves towards more integrated and application-oriented themes. Digital healthcare, artificial intelligence, and digital twin occupy central positions. Increasing attention is also given to predictive models and data analytics, as well as immersive and interactive technologies such as virtual reality. The reappearance of blockchain at this stage points to rising interest in trust, data integrity, and system security in healthcare environments.

Complementing the analyses of thematic structure and evolution, the trend chart offers a forward-looking perspective on research into digital technologies supporting predictive healthcare (Figure 10).

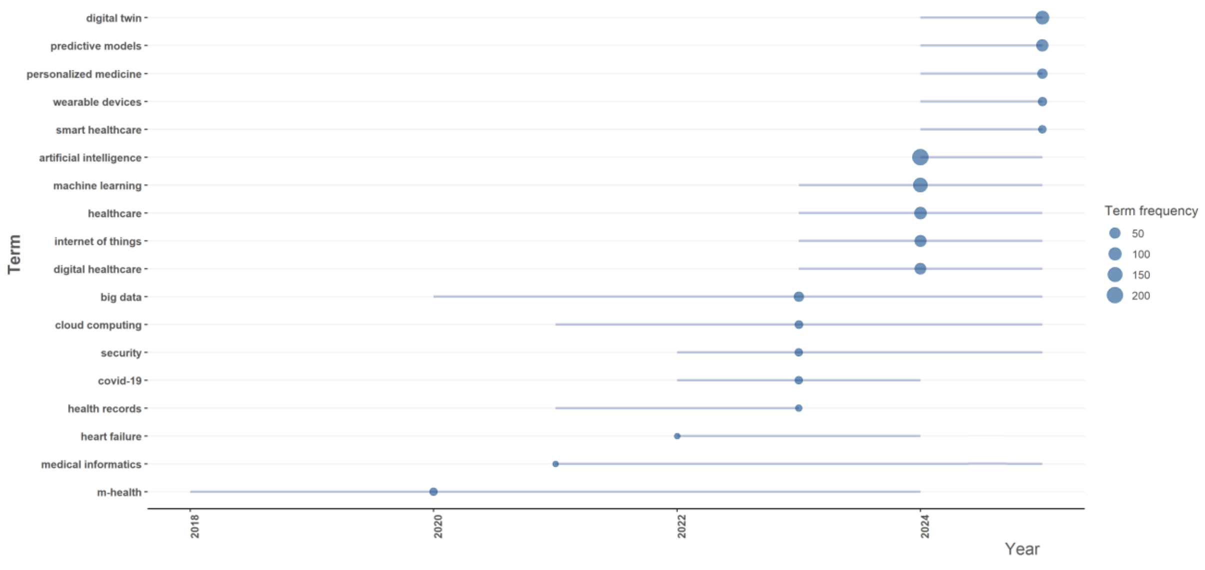

Figure 10. Research trends in predictive healthcare digital technologies.
[Source: authors' own elaboration using software RStudio – Biblioshiny 5.2.1]

It shows that in recent years topics related to artificial intelligence and machine learning have become increasingly dominant, closely linked with predictive models and digital healthcare. At the same time, the growing visibility of themes such as digital twin, personalised medicine, wearable devices, and smart healthcare points to a shift towards more integrated, personalised, and continuously monitored healthcare solutions. The stable presence of topics related to cloud computing, the internet of things, and data security further highlights that the future development of predictive systems relies strongly on robust digital infrastructure and trust in data processing.

EMERGING THEMATIC AREAS

The results of the bibliometric analysis clearly indicate that the concept of digital twins currently represents one of the most rapidly developing research trends within the field of digital technologies supporting predictive healthcare. The trend analysis presented in Figure 10 shows that interest in digital twin–related research has increased markedly in recent years. This development is closely linked to the growing role of artificial intelligence and machine learning methods, which form the foundation of contemporary predictive models. The increasing frequency of terms such as digital healthcare and predictive models further confirms a shift in the research paradigm towards solutions focused on forecasting health processes and adopting a more proactive approach to patient care.

At the same time, the trend analysis reveals a gradual shift in research interests towards healthcare models based on greater data integration and continuous monitoring. More frequent references to personalised medicine, wearable devices and smart healthcare systems suggest that digital twins are no longer viewed as isolated analytical tools. Instead, they are increasingly embedded within broader patient data ecosystems. These ecosystems enable the integration of information derived from multiple sources and its application in diagnostic and decision-making processes. The stable presence of themes related to cloud infrastructure, the Internet of Things and data security highlights the importance of robust and trustworthy technological foundations for the further development of predictive healthcare systems.

On the basis of the obtained results, three emerging thematic areas were identified that particularly reflect current and future directions of research into digital technologies for predictive healthcare. The first area focuses on digital twins and integrated patient data ecosystems, including interoperability, large-scale data analytics and clinical decision support. The second area concerns predictive and preventive digital twins aimed at care personalisation, disease prevention and the optimisation of health trajectories. The third area addresses treatment planning and patient response simulation using digital twins, with particular emphasis on clinical, surgical and rehabilitation applications. A detailed discussion of each of these thematic areas is provided in the following subsections.

Topic 1. Digital Twins and Integrated Patient Data Ecosystems

Digital twins that use artificial intelligence and wearable IoMT sensors are increasingly applied in healthcare. They enable the simulation of disease progression and the planning of therapeutic interventions. They also support predictive medical analytics, the analysis of large clinical datasets, and clinical decision support systems (Cappon & Facchinetti, 2024). This allows the delivery of virtual medical services and the precise adjustment of therapies to individual patient needs.

Models of treatment response based on physical principles and analysed across multiple scales strengthen clinical decision support systems. They improve the prediction of treatment response, clinical risk, and disease trajectories. They also facilitate the assessment of adverse event risk and the selection of therapeutic strategies (Trayanova & Prakosa, 2024). Predictive analytics based on IoMT digital twins support cloud-based and blockchain-enabled remote medical care and data-driven healthcare decision-making using large datasets (Jain et al., 2024).

Wearable IoMT sensors and blockchain technology are also used to simulate clinical procedures. They enable remote and personalised patient treatment. They also support care and recovery processes through cloud-based digital twins (Ghaempanah et al., 2024). Federated and swarm learning approaches enable the analysis of large, multimodal clinical datasets. These solutions support disease diagnosis and prognosis and the development of predictive patient digital twins (Chakshu & Nithiarasu, 2024). The analysis and interoperability of patient engagement data enable more personalised clinical decision-making in virtual environments (Samei, 2025).

Real-time analysis of large clinical datasets enables the simulation of clinical procedures, surgical interventions, and treatment responses. This supports the optimisation of patient care and recovery processes (de Oliveira El-Warrak & Miceli de Farias, 2025). Cyber-physical medical systems and extended reality technologies support treatment planning and disease progression forecasting. They facilitate diagnosis, prevention, and the evaluation of treatment effectiveness. They also enable continuous monitoring of patient vital signs (Nadeem et al., 2025).

Artificial intelligence and machine learning-based digital twins integrate different types of patient physiological data. This increases the accuracy of predicting severe disease conditions and improves diagnostic quality. These solutions also support real-time remote patient monitoring (Upadrista et al., 2025). Real-time patient data analysis enables the development of immersive healthcare delivery within the healthcare metaverse. It supports personalised treatment and disease diagnosis (Jeong & Lee, 2025).

Advanced digital twin models use deep learning and reinforcement learning to analyse patient health data. They enable the simulation of disease progression and treatment response. They also support the monitoring of medication adherence and therapy planning. They facilitate early disease detection and the adjustment of care to individual patient needs (Rizzo, 2025). Digital twins are also used in virtual simulations of surgical procedures. They support treatment, diagnosis, monitoring, and health status forecasting. As a result, they contribute to improved decision-making in healthcare systems (Xue et al., 2025).

Topic 2. Predictive and Preventive Digital Twins for Personalised Healthcare

Simulations of healthcare ecosystems based on cloud computing, blockchain technology, and IoT enable the creation of interoperable and immersive healthcare environments. These solutions support the modelling and prediction of healthcare service delivery in extended reality settings. They also facilitate diagnostic and therapeutic interventions and improve patient health status and treatment outcomes within the healthcare metaverse (Li et al., 2024b). Personalised virtual healthcare services integrate large volumes of patient medical data within extended reality environments. This enables more precise and individualised approaches to healthcare delivery (Ling & Butakov, 2024). Effective therapy planning and disease progression modelling require access to large-scale physiological and clinical data. They also involve predictive disease modelling, virtual clinical practice simulations, and continuous patient health monitoring and analysis (Bhagirath et al., 2024).

Predictive artificial intelligence-based digital twins enable the simulation of patient disease progression. They support treatment outcome prediction and preventive actions. They also facilitate clinical and healthcare decision-making, therapeutic target identification, and the optimisation of medication adherence (Li et al., 2025). Digital twins that integrate medical imaging and machine learning allow the monitoring of patient-specific pathological conditions. They support disease risk prediction, treatment planning, and clinical decision support systems. As a result, they contribute to improved treatment outcomes and greater accuracy in medical decision-making (Kimpton et al., 2025).

Connected healthcare digital twins that use explainable artificial intelligence and cyber-physical systems enable the analysis of multidimensional and multimodal patient health data. These solutions support real-time remote diagnosis, treatment, therapy, and rehabilitation. They rely on IoT sensors and actuators as well as blockchain technology to monitor and predict patient health status (Araghi et al., 2025).

Predictive digital twins based on deep learning and machine learning support the analysis and modelling of timely surgical interventions. They enable real-time monitoring of patient physiological signals. They support medical decision support systems based on support vector machines and k-nearest neighbour methods. They also facilitate early disease and abnormality detection using random forests and convolutional neural networks. These approaches contribute to improved treatment protocols and survival rates (Khan et al., 2025). The simulation and prediction of individual patient health trajectories support precise diagnosis and medical intervention planning. The use of multidimensional physiological and disease-related data enables the development of personalised treatment models. These solutions are applied within predictive digital twins based on explainable artificial intelligence. They support tailored health recommendations and the optimisation of clinical practice (Sel et al., 2025).

Digital twins that use reinforcement learning and machine learning support personalised preventive treatment and targeted therapies. They enable virtual patient diagnosis and prognosis prediction. They improve the accuracy of therapeutic decisions and surgical planning based on data from wearable IoT sensors. They also integrate the fusion and analysis of multimodal clinical and imaging data in real time. These solutions support treatment response modelling using generative adversarial and convolutional neural networks (Shen et al., 2025).

The healthcare metaverse and deep learning-based digital twins enable remote, immersive, and evidence-based rehabilitation. They allow real-time monitoring of patient health status, engagement, and responses to therapy. Wearable IoT sensors are used to support disease prevention and diagnosis (Chen et al., 2025a). Simulations of disease progression and patient responses, as well as the modelling of surgical and therapeutic interventions, enable more accurate treatment response prediction. They contribute to improved therapy effectiveness, clinical outcomes, and diagnostic and prognostic accuracy (Wu et al., 2025). Simulations of surgical procedures and predictive modelling of treatment pathways based on wearable IoT sensors support clinical decision-making. They also contribute to improved health outcomes and the monitoring of therapeutic intervention effects (Vaughan Robinson et al., 2025).

Topic 3. Digital Twin–Based Treatment Planning and Patient Response Simulation

Personalised predictive digital twins in healthcare, based on IoMT sensors and blockchain technology, are increasingly used in disease diagnosis. These solutions enable the interoperability and analysis of large healthcare and physiological datasets. They also support computer-aided diagnostic systems and medical decision support (Sadeghi & Mahmoudi, 2024). Modelling physiological and diagnostic process data using artificial intelligence and generative adversarial networks, combined with medical imaging analysis based on deep learning, reinforcement learning, and machine learning, enables the simulation and prediction of personalised therapeutic decisions (Jean-Quartier et al., 2024). Artificial intelligence-based digital twins support treatment planning, the simulation of patient responses to interventions, and disease progression modelling. They also enable the analysis of dynamic, multivariate patient state data and support clinical decision-making (Wentzel et al., 2025).

Healthcare delivery simulations, real-time medical image analysis, and the study of disease trajectories and treatment responses support better tailoring of interventions for at-risk patients. These approaches also contribute to improved treatment outcomes, as well as disease prediction, prevention, prognosis, and therapy planning (Li et al., 2025). Artificial intelligence-based digital twins support medical decision-making and healthcare process modelling. Therapy simulations in the healthcare metaverse, using extended reality technologies, enable forecasting of patient treatment outcomes. Treatment recommendation analysis based on IoMT sensors and cloud computing supports real-time diagnostic prediction. These solutions improve clinical decision-making, patient care, and the development of healthcare services in the metaverse (Sharma et al., 2025). Patient treatment modelling and simulation using IoMT sensors, together with real-time health data from wearable IoT devices, enable continuous patient monitoring. They support early disease detection, shorter surgical and recovery times, and improved surgical performance and patient outcomes (Asciak et al., 2025).

Internet of Medical Things solutions, based on wearable sensors and cloud computing, enable the simulation of patient care and medical diagnosis. They play a key role in remote, real-time monitoring of vital signs and patient health status. They also support early detection and prediction of health problems (Mistry & Dafoulas, 2025). Medical extended reality metaverse environments and predictive healthcare digital twins based on artificial intelligence support disease diagnosis, therapeutic decision-making, and treatment monitoring. They also enable prognosis and the simulation of preventive and rehabilitative interventions. The interoperability of physiological data collected from IoMT sensors, supported by blockchain technology, enables more coherent clinical data analysis. These solutions support virtual medical procedures, immersive rehabilitation, and the optimisation of diagnosis and therapy. They also improve healthcare delivery, patient engagement, and clinical outcomes, while supporting recovery processes and personalised healthcare interventions (Morone et al., 2025). Immersive simulations of remote surgical procedures using digital twins, artificial intelligence, and virtual medical systems enable patient motion tracking through IoT sensors and actuators (Kumar Jagatheesaperumal et al., 2024).

Modelling patient physiological state and treatment outcome data supports post-surgical care and recovery simulations. It also enables long-term forecasting of physiological parameters and therapeutic responses (Halder et al., 2025). Remote monitoring of patient vital signs and health status using IoT sensors and actuators, together with clinical data interoperability, enables the simulation of precise surgical interventions. These solutions can be used for early disease prevention, detection, diagnosis, and progression monitoring (Kumar et al., 2025). They also enable treatment planning, optimisation of therapeutic outcomes using machine learning-based digital twins, disease diagnosis, disease progression monitoring, and medication adherence assessment (Fatouros et al., 2025).

DISCUSSION

Taken together, the obtained results suggest that research on digital technologies supporting predictive healthcare is centred on a rapidly developing ecosystem that combines large-scale medical data analytics, machine learning algorithms and simulation-based technologies. Both the bibliometric and qualitative analyses indicate that solutions based on digital twins and Internet of Medical Things systems play a dominant role in this area, forming the foundation of cyber–physical healthcare systems (Shoukat et al., 2024).

The findings show that a substantial proportion of the analysed literature focuses on the application of deep learning algorithms, particularly convolutional neural networks, for early and accurate disease prediction and diagnosis. These methods are applied to both clinical and medical imaging data, enabling earlier detection of pathological changes and supporting therapeutic decision-making processes (Kulkarni et al., 2024; Badjatia et al., 2025). The observed link between artificial intelligence algorithms and the digital twin concept confirms the growing role of simulation-based and immersive environments in predictive healthcare research (Li et al., 2024a; Wang et al., 2024).

One clearly identifiable research direction emerging from the analysis concerns the integration of digital twins with cloud-based architectures and multi-agent systems, which appears to support more continuous and adaptive healthcare workflows. The reviewed studies indicate that such integration enables continuous processing of biosensor data and contributes to the optimisation of healthcare workflows (Lakhan et al., 2024). In parallel, an expanding body of research links digital twin technologies with distributed ledger solutions, aiming to enhance data security, improve interoperability and strengthen trust within patient care and treatment processes (McCourt, 2024).

The thematic analysis also highlights the increasing importance of virtual patient modelling and the prediction of treatment outcomes. Numerous publications emphasise the role of big healthcare data analytics and synthetic data in simulating disease trajectories and patient responses to therapeutic interventions. These approaches are particularly relevant for treatment planning and for anticipating disease progression (Delerm & Pilottin, 2024; Zerrouk et al., 2024). Within research on virtual clinical environments, solutions employing interoperable data and feedback mechanisms, including haptic feedback, are also emerging, supporting diagnostic procedures and therapy planning (Li et al., 2024b).

The analysed publications further demonstrate that, alongside advanced deep learning methods, classical machine learning algorithms and optimisation techniques remain relevant for improving diagnostic accuracy and supporting personalised treatment planning (Sultanpure et al., 2024). At the same time, digital twins are increasingly applied in remote medical rehabilitation and long-term patient monitoring, indicating an expansion of their use beyond acute care contexts (Xie et al., 2025).

Another important theme identified in the results is the development of personalised health trajectories and preventive planning. Data-driven approaches based on large healthcare datasets enable the assessment of individual health risks, the simulation of preventive interventions and the optimisation of treatment outcomes over longer time horizons (Yurkovich et al., 2024; de Oliveira El-Warrak & Miceli de Farias, 2025). In this context, artificial intelligence-supported healthcare models gain prominence by enabling real-time diagnosis, personalised therapies and advanced forms of telepresence (Arastouei & Khan, 2025).

The analysis confirms the growing significance of integrating blockchain technologies with cloud computing, IoT systems and wearable devices to enable secure remote patient monitoring and data-driven clinical process simulation (Alhamam et al., 2025). Increasing attention is also given to advanced learning techniques, including reinforcement learning and generative adversarial networks, which enhance the predictive capabilities of digital healthcare systems (Böttcher et al., 2025; Rizzo, 2025).

The obtained results align with a broader stream of research addressing disease prevention, diagnosis and treatment through digital technologies (Núñez-Merino et al., 2024). In particular, publications focusing on blockchain- and cloud-based IoMT systems indicate improvements in diagnostic accuracy, prognostic performance and therapeutic effectiveness (Gana & Jamil, 2025). The use of digital twins for the analysis of clinical and medical imaging data is also increasingly applied to the early detection of clinical deterioration (Badjatia et al., 2025).

The findings further confirm that earlier studies concentrated primarily on patient digital twins and disease risk prediction within metaverse environments (Ma et al., 2024; Kulkarni et al., 2024). At the same time, research advanced solutions based on wearable sensor data and neural networks for smart healthcare systems (Liu et al., 2024), as well as cloud and edge computing architectures supporting the evaluation of medical procedures (Akbarialiabad et al., 2024).

The growing role of artificial intelligence in tailoring therapeutic interventions, managing chronic conditions and supporting virtual clinical practice is also clearly evident (Mosquera-Lopez & Jacobs, 2024; Hu & Zheng, 2024). Recent studies increasingly identify the automation of clinical processes as a fundamental pillar of future healthcare architectures. Within this context, decision-support systems based on multi-agent models are gaining prominence due to their capacity to incorporate patient-specific data and situational factors into clinical reasoning in a flexible manner (Qiu et al., 2024). These developments are further complemented by blockchain-based metaverse solutions, which extend clinical decision support by embedding diagnostic and therapeutic services within secure, transparent and trusted digital environments (Ling & Butakov, 2024).

Recent contributions further underline the role of digital twin-based simulation frameworks in enhancing treatment effectiveness, examining healthcare operational processes and supporting improvements in organisational performance across healthcare systems (Penverne et al., 2024). Cyber–physical healthcare systems increasingly integrate data from wearable sensors with deep learning algorithms. Such configurations enable the virtual support of therapeutic processes and allow for continuous monitoring of patient health status (Xing et al., 2024). In parallel, Internet of Things solutions enhanced with artificial intelligence are gaining importance in predictive healthcare. These systems facilitate the early identification of disease-related changes and support anticipatory models of healthcare delivery (Shehzad et al., 2024; Arunprasath & Annamalai, 2024).

Taken together, the results indicate that predictive healthcare is moving towards increasingly interconnected and analytically driven systems. Digital twins, artificial intelligence and IoT technologies are no longer developed in isolation, but function as mutually reinforcing components of broader computational infrastructures. The literature reviewed in this study points to an increasing focus on integrated solutions in predictive healthcare. These approaches aim to support more individualised care pathways and enable earlier identification of potential health risks. They also contribute to clinical decision-making that is more anticipatory rather than reactive. At the same time, the results consistently reveal a persistent gap between conceptual and technological developments and their routine application in everyday clinical practice. This observation highlights the need for further validation studies, research oriented towards implementation, and closer cooperation between technological innovation and clinical stakeholders.

CONCLUSIONS

The bibliometric and qualitative analyses conducted in this study provide a structured overview of current research directions in digital technologies supporting predictive healthcare. The results clearly indicate the central role of digital twins. These systems increasingly serve as integrative frameworks for artificial intelligence, machine learning and Internet of Medical Things solutions. The analysed literature shows a clear shift away from isolated technological applications towards complex and interoperable patient data ecosystems. Such ecosystems enable continuous health monitoring, disease trajectory modelling and real-time clinical decision support.

The distinction of three emerging thematic areas helps to clarify how this research field is organised and how it is evolving. The first area centres on digital twins and integrated patient data ecosystems, drawing attention to the role of data interoperability and the analysis of large-scale health data. The second area addresses predictive and preventive applications of digital twins, with an emphasis on care personalisation and early health risk identification. The third area concerns treatment planning and patient response simulation, particularly in clinical, surgical and rehabilitation contexts. Across all thematic areas, predictive modelling is becoming a central element of contemporary healthcare research. Simulation environments are playing a growing role in shaping new approaches to the organisation and delivery of healthcare services.

The results suggest that many technological innovations have not yet been fully embedded in everyday clinical practice. There remains a noticeable distance between conceptual advances and their practical application. This points to the need for further validation in real clinical settings. More implementation-oriented research is required. Organisational conditions also deserve greater attention. Ethical and regulatory issues should be addressed more explicitly. Future studies need to focus on how digital twin solutions fit into existing clinical workflows. Decision-making processes in practice should be a central reference point. Such an approach is necessary to achieve the full benefits of predictive healthcare.

Several limitations of this study should be acknowledged. The analysis was limited to publications indexed in the Scopus and Web of Science databases. As a result, some implementation-oriented studies and grey literature may not have been captured. The bibliometric and qualitative methods used in this study enable the examination of publication dynamics and the identification of dominant thematic patterns. They do not, however, provide direct evidence of the clinical effectiveness of the analysed solutions. The field of predictive healthcare technologies is developing rapidly. Consequently, the patterns identified in this study may evolve as new evidence becomes available. This does not call into question the overall robustness of the results. However, the findings should be interpreted with appropriate caution. The identified limitations are also relevant when outlining priorities for further research.

IMPLICATIONS FOR RESEARCH AND APPLICATION

The conducted analysis makes it possible to indicate several observations relevant for further research on digital technologies supporting predictive healthcare. From a research perspective, further investigation of digital twins in everyday clinical environments is needed. Existing studies provide limited insight into how these solutions operate in routine care. Future research could therefore examine their alignment with established diagnostic and therapeutic workflows. Empirical studies are also required to explore organisational and technological factors that shape the adoption of digital twin technologies in healthcare practice.

From an application perspective, the findings highlight the importance of coherent and interoperable patient data ecosystems. The effective use of digital twins depends on appropriate digital infrastructure and on solutions that enable the secure integration of data from multiple sources. At the same time, implementation processes should take into account the organisational realities of healthcare institutions and the readiness of medical staff to work with advanced analytical tools. Attention to these aspects may support a more gradual and realistic use of digital technologies in predictive healthcare.

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All correspondence should be addressed to
George Lăzăroiu
Curtin University, Australia
Toronto Metropolitan University, Canada
Cardiff Metropolitan University, United Kingdom
Bentley, WA 6102, Australia
phd_lazaroiu@yahoo.com

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