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Mathematical Modeling and Artificial Intelligence in Smart Food Systems: A Bibliometric and Science Mapping Analysis

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Abstract
This study analyzes the global development of mathematical modeling and artificial intelligence in smart food systems using bibliometric and science mapping approaches. Data were collected from 561 Scopus-indexed documents published between 1994 and 2026 and analyzed using Bibliometrix and Biblioshiny. The analysis covers publication trends, leading sources, country contributions, trend topics, thematic mapping, thematic evolution, co-occurrence networks, and Multiple Correspondence Analysis. The results show rapid publication growth, particularly after 2020, driven by machine learning, artificial intelligence, precision agriculture, predictive modeling, and smart agriculture. The conceptual structure reveals two dominant paradigms: a data-driven approach centered on AI and machine learning, and a model-driven approach emphasizing mathematical modeling, simulation, optimization, and decision-making. The findings indicate increasing convergence between these paradigms, leading to the proposed concept of Hybrid Intelligent Food Systems, which integrates AI-based prediction with mathematical optimization and interpretability to support adaptive, efficient, and sustainable food systems.

Keywords: artificial intelligence; bibliometric analysis; mathematical modeling; machine learning; smart food systems

Abstrak
Penelitian ini menganalisis perkembangan global pemodelan matematika dan kecerdasan buatan dalam smart food systems menggunakan pendekatan bibliometrik dan science mapping. Data diperoleh dari 561 dokumen terindeks Scopus yang diterbitkan pada periode 1994–2026 dan dianalisis menggunakan Bibliometrix serta Biblioshiny. Analisis mencakup tren publikasi, sumber publikasi utama, kontribusi negara, trend topics, thematic mapping, thematic evolution, co-occurrence network, dan Multiple Correspondence Analysis. Hasil penelitian menunjukkan peningkatan publikasi yang pesat, terutama setelah tahun 2020, didorong oleh perkembangan machine learning, artificial intelligence, precision agriculture, predictive modeling, dan smart agriculture. Struktur konseptual menunjukkan dua paradigma utama, yaitu pendekatan data-driven yang berpusat pada AI dan machine learning, serta pendekatan model-driven yang menekankan pemodelan matematika, simulasi, optimasi, dan pengambilan keputusan. Temuan ini menunjukkan adanya konvergensi kedua paradigma tersebut dan mengarah pada konsep Hybrid Intelligent Food Systems untuk mendukung sistem pangan yang adaptif, efisien, dan berkelanjutan.

Kata Kunci: analisis bibliometrik; kecerdasan buatan; pemodelan matematika; machine learning; smart food systems

1. INTRODUCTION

Digital transformation has driven significant changes in modern food systems to address global challenges such as population growth, climate change, resource limitations, and increasing supply chain complexity (Hassoun et al., 2023; Vahdanjoo et al., 2025). In this context, the concept of smart food systems has emerged, referring to food systems that integrate digital technologies, data analytics, and automation to enhance efficiency, productivity, quality, and sustainability throughout the food value chain (Hassoun et al., 2023).

The development of smart food systems is supported by various technologies, including the Internet of Things (IoT), smart sensors, remote sensing, hyperspectral imaging, cloud computing, and big data analytics (Hassoun et al., 2023; Vahdanjoo et al., 2025). These technologies generate vast amounts of data that can be utilized for environmental monitoring, yield prediction, quality control, and the real-time optimization of food production and distribution processes (Hassoun et al., 2023). However, the availability of large and complex datasets necessitates analytical approaches capable of transforming raw data into meaningful information and actionable decisions (Vahdanjoo et al., 2025).

In this field, mathematical modeling and artificial intelligence (AI) have emerged as two major approaches that are developing in parallel (Ahmed et al., 2026). Mathematical modeling is employed to understand system dynamics, perform simulations, and identify optimal solutions through optimization techniques, dynamic systems, stochastic models, and predictive modeling approaches (Ahmed et al., 2026; Kostić et al., 2026). Meanwhile, AI particularly machine learning and deep learning enables the identification of complex patterns, automated classification, and highly accurate predictions based on large-scale datasets (Ahmed et al., 2026).

Recent developments indicate an increasingly strong convergence between these two approaches (Ahmed et al., 2026; Vahdanjoo et al., 2025). Mathematical modeling provides capabilities for interpretation, simulation, and optimization, whereas AI offers the ability to learn from complex and high-dimensional data (Ahmed et al., 2026). The integration of these approaches enables the development of systems that not only generate accurate predictions but also support more adaptive and optimal decision making within modern food systems (Ahmed et al., 2026; Kostić et al., 2026).

In line with these developments, the number of publications addressing AI, mathematical modeling, and smart food systems has increased substantially in recent years. Numerous bibliometric studies have examined AI in agriculture, precision agriculture, smart farming, and the digital transformation of the food sector. However, most of these studies have focused on specific domains and have not explicitly explored the relationship between mathematical modeling and AI within the broader framework of smart food systems (Ahmed et al., 2026). Consequently, the conceptual structure of the research field, the patterns of thematic evolution, and future research directions remain insufficiently understood from a comprehensive perspective.

Based on these research gaps, this study aims to analyze the global development of research on mathematical modeling and artificial intelligence in smart food systems using a bibliometric and science mapping approach based on Scopus data. The analysis is conducted to identify publication trends, leading publication sources, country contributions, the evolution of research themes, the conceptual structure of the field, and the intellectual evolution that has shaped this research landscape.

This study offers four main contributions. First, it provides a comprehensive mapping of the global development of research on the integration of mathematical modeling and AI within smart food systems. Second, it identifies the major themes and conceptual structures that underpin this research field. Third, it reveals the existence of two dominant paradigms namely, the model-driven approach and the data-driven approach and highlights the role of machine learning as a conceptual bridge between them. Fourth, it proposes a future research direction toward Hybrid Intelligent Food Systems, a framework that integrates the predictive capabilities of AI with the optimization, simulation, and interpretability strengths of mathematical modeling.

2. RESEARCH METODHOLOGY

Research Design

This study employs a bibliometric approach combined with science mapping to analyze the development of research on the integration of mathematical modeling and artificial intelligence within smart food systems (Donthu et al., 2021). Bibliometric analysis is used to evaluate scientific productivity, research trends, and knowledge structures, while science mapping is applied to visualize conceptual relationships and the evolution of research themes (Cobo et al., 2011).

Data Source and Search Strategy

Bibliographic data were retrieved from the Scopus database in April 2026. Scopus was selected due to its extensive multidisciplinary journal coverage, comprehensive metadata, and its status as one of the most widely used databases in bibliometric research (Martín-Martín et al., 2018). Furthermore, Scopus provides strong representation in the fields of applied mathematics, artificial intelligence, agriculture, and food technology, making it particularly suitable for the objectives of this study. The search strategy was designed to integrate three key concepts mathematical modeling, artificial intelligence, and smart food systems using the following query:

TITLE-ABS-KEY ((“mathematical model" OR "optimization model" OR "computational model" OR "simulation model" OR "predictive model") AND ("artificial intelligence" OR "machine learning" OR "deep learning") AND ("food processing" OR "food system" OR "food supply chain" OR "food engineering" OR "smart agriculture" OR "precision agriculture")) AND NOT TITLE-ABS-KEY (medicine OR medical OR health OR disease OR patient OR hospital OR bioinformatics)

Data Processing and Validation

The metadata were exported in CSV format and processed using the Bibliometrix package and the Biblioshiny interface in the R software environment (Aria & Cuccurullo, 2017). The analyzed dataset included bibliographic information such as titles, abstracts, keywords, authors, affiliations, publication sources, publication years, citations, and references.

Bibliometric Analysis

Bibliometric analysis was conducted to evaluate the general characteristics of the publications that constitute this research field. The main indicators analyzed included: 1) Annual Scientific Production, 2) Most Relevant Sources, 3) Country Scientific Production, 4) Citation Analysis, and 5) Trend Topics.

Science Mapping Analysis

To gain a deeper understanding of the intellectual and conceptual structure of the research field, a science mapping analysis was conducted (Donthu et al., 2021) incorporating several key approaches: 1) Thematic Mapping, to classify themes based on their levels of centrality and density, 2) Thematic Evolution, to examine changes in research themes over time, 3) Co-occurrence Network Analysis, to map relationships among keywords, and 4) Factorial Analysis (MCA), to identify thematic clusters and reveal the conceptual structure of the research domain.

Research Question

This study was designed to address three main research questions:

1. How has the scientific literature on mathematical modeling and artificial intelligence in smart food systems evolved over time?
2. What themes, conceptual structures, and intellectual developments have shaped this research field?
3. What research directions and opportunities hold the greatest potential for advancing the development of smart food systems in the future?

3. RESULTS AND DISCUSSIONS

Main Information about Dataset

Figure 1. Main Information

The search conducted in the Scopus database retrieved 561 documents published between 1994 and 2026, originating from 392 publication sources. The dataset involved 2,319 authors, included a total of 27,552 references, and exhibited an annual publication growth rate of 15.26%.

The high annual growth rate indicates that research on the integration of mathematical modeling and artificial intelligence within smart food systems has expanded rapidly in recent years. This growth reflects increasing interest in the application of digital technologies, data analytics, and intelligent systems to enhance efficiency, productivity, and sustainability across the food sector.

The average of 4.54 co-authors per document suggests that this research field is inherently multidisciplinary, involving collaboration among experts in mathematics, computer science, engineering, agriculture, and food technology. Furthermore, an international co-authorship rate of 23.89% indicates that the development of smart food systems has become a global research agenda, fostering cross-national collaboration to address contemporary food-related challenges.

Annual Scientific Production

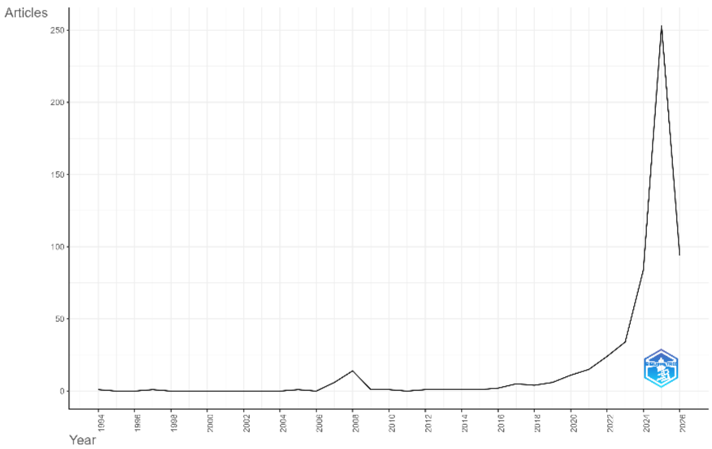

Figure 2. Annual Scientific Production

Figure 2 illustrates that research on mathematical modeling and artificial intelligence in smart food systems has experienced substantial growth throughout the observation period. Although publications on this topic first appeared in 1994, a significant increase became evident only after 2020.

During the period 1994 - 2015, the number of publications remained relatively low and was primarily dominated by studies focusing on decision support systems, simulation techniques, and conventional optimization approaches. The period 2016 - 2020 witnessed an increase in research activity, driven by advances in machine learning, big data analytics, the Internet of Things (IoT), and precision agriculture.

The most pronounced surge in publications occurred during 2021 - 2025, indicating that the integration of AI and mathematical modeling has become a major focus in the digital transformation of food systems. Advances in sensor technologies, cloud computing, and machine learning algorithms have accelerated the adoption of data-driven systems for prediction, optimization, and real-time decision-making.

Overall, the publication trend reveals a transition from predominantly model driven approaches toward a stronger integration with the data-driven paradigm, which has become a fundamental pillar in the development of modern smart food system.

Most Relevant Sources

The analysis of publication sources indicates that research on mathematical modeling and artificial intelligence in smart food systems has evolved as a highly multidisciplinary field, driven by the interaction of agriculture, computer science, engineering, and food science.

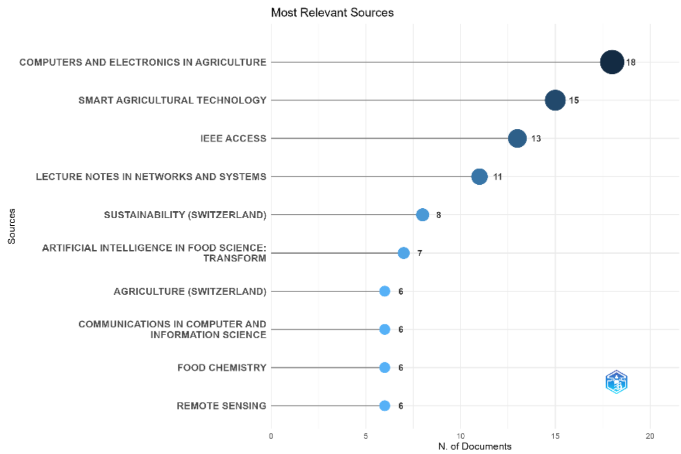

Figure 3. Most Relevant Sources

Based on Figure 3, Computers and Electronics in Agriculture is the most productive publication source, followed by Smart Agricultural Technology, Remote Sensing, Agriculture, and IEEE Access. The prominence of these journals suggests that the development of smart food systems is strongly driven by advances in digital technologies, automation, smart sensors, and data analytics.

The presence of AI and computer science-oriented journals, such as IEEE Access and Communications in Computer and Information Science, highlights the growing role of machine learning, deep learning, and data analytics in modern food systems. Meanwhile, the emergence of journals such as Artificial Intelligence in Food Science and Food Chemistry indicates that AI applications are expanding beyond agricultural production to encompass food processing, quality control, and food quality assessment.

These findings suggest that the field is increasingly moving toward the development of integrated systems that combine the predictive capabilities of AI with the optimization and simulation strengths of mathematical modeling.

Country Scientific Production

The distribution of publications by country indicates that research on mathematical modeling and artificial intelligence in smart food systems has expanded globally, although it remains concentrated in a limited number of countries with strong research capabilities and advanced technological infrastructures.

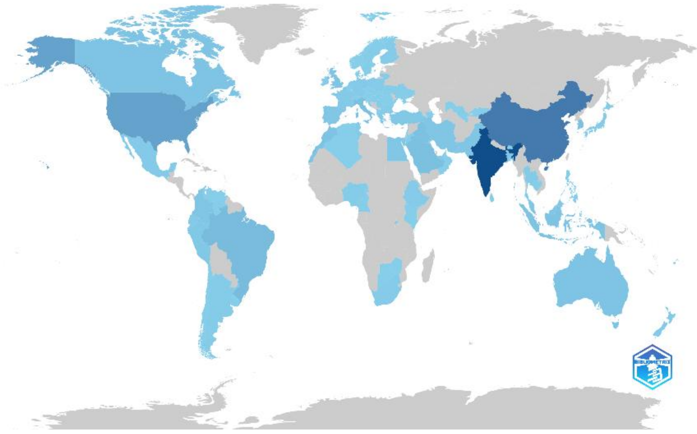

Figure 4. Country Scientific Production

Based on Figure 4, India, China, and the United States are the leading contributors to this research field. The dominance of these three countries reflects substantial investments in research, advances in digital technologies, and strategic efforts to enhance agricultural productivity and food security through the application of AI and intelligent systems.

Interestingly, the significant contributions of India and China suggest that the center of research development is no longer dominated exclusively by Western countries but is increasingly shifting toward Asia. This trend indicates that the digital transformation of the food sector has become a critical priority for countries with large populations and growing food demands.

Trend Topic Analysis

The trend topics analysis reveals that research on mathematical modeling and artificial intelligence in smart food systems has undergone dynamic changes throughout the observation period.

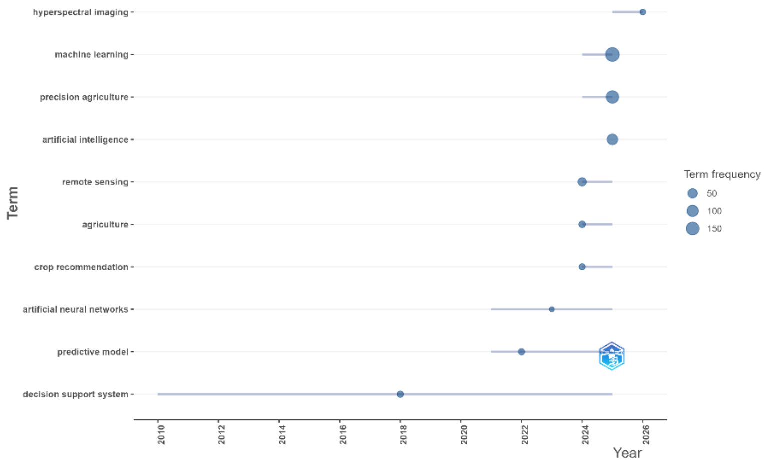

Figure 5. Trend Topic

During the early phase, research was dominated by decision support systems, which focused on the use of mathematical models and computational systems to support decision making processes. Entering the 2021 - 2023 period, research themes began to shift toward predictive models and artificial neural networks, reflecting the growing adoption of data driven approaches in food systems.

The most significant transformation occurred during 2024 - 2026, marked by the emergence of themes such as machine learning, artificial intelligence, precision agriculture, remote sensing, and crop recommendation. The prominence of these topics indicates that research has evolved toward systems capable of performing data driven prediction, monitoring, and automated decision making.

Thematic Map Analysis

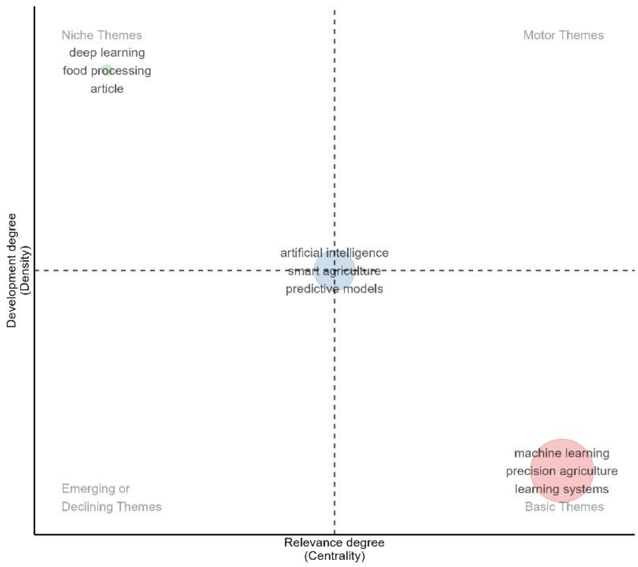

Figure 6. Thematic Map

The thematic map was used to evaluate the position and maturity of research themes based on their levels of centrality and density (Callon et al., 1991). The results indicate that machine learning, precision agriculture, and learning systems are classified as basic themes, highlighting their central role in the development of this research field.

The dominance of these themes suggests that machine learning has become a fundamental pillar in the development of smart food systems. In addition, themes such as artificial intelligence, smart agriculture, and predictive models exhibit strong connections with a wide range of other research topics, highlighting the strategic role of AI in the transformation of modern food systems.

Meanwhile, deep learning and food processing emerge as niche themes, indicating that these topics have reached a relatively mature stage of development while maintaining more limited connections with other thematic areas. These findings suggest that research is progressing through a combination of advances in AI technologies and the expansion of their applications across various sectors of food systems.

Overall, the thematic map reveals that this research field is evolving toward increasingly integrated systems, with AI serving as the primary driving force and mathematical modeling providing essential support for optimization and decision making processes.

Thematic Evolution Analysis

The thematic evolution analysis was conducted to examine how research themes have developed, transformed, and interconnected throughout the observation period. The results reveal that research on mathematical modeling and artificial intelligence in smart food systems has undergone a clear evolution, progressing from conventional computational approaches toward intelligent food systems that integrate predictive capabilities, optimization techniques, and data driven decision making processes.

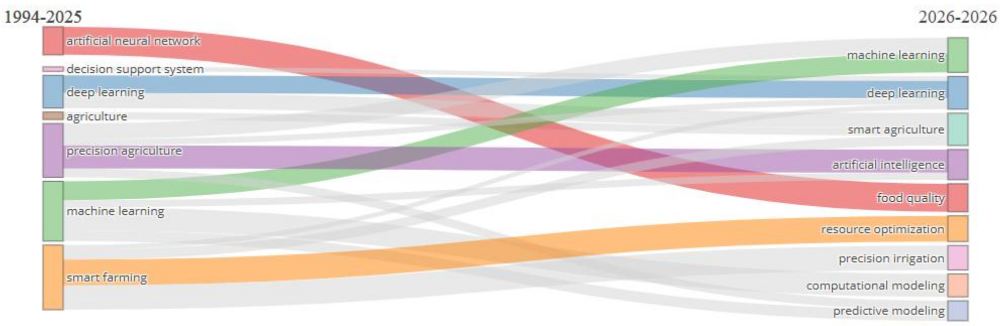

Figure 7. Thematic Evolution

During the early stage, the dominant themes were decision support systems, artificial neural networks, and agriculture, reflecting a focus on decision support and the application of relatively simple computational models. As data availability and computational capacity increased, research evolved toward machine learning, deep learning, and precision agriculture, representing the growing adoption of data driven approaches.

In the most recent phase, themes such as smart agriculture, predictive modeling, computational modeling, and resource optimization have emerged as major research priorities. The appearance of these themes indicates that the field is no longer focused solely on AI-based predictive capabilities but is increasingly integrating optimization and simulation approaches derived from mathematical modeling.

Overall, the thematic evolution reveals a convergence between the model driven and data driven paradigms, forming the foundation for the next generation of smart food systems that are more adaptive, efficient, and sustainable.

Co-occurrence Network Analysis

The co-occurrence network analysis was conducted to map the conceptual relationships among keywords based on their co-appearance within the analyzed publications (van Eck & Waltman, 2010). The resulting network reflects the intellectual structure of the research field and highlights the themes that serve as central drivers in the development of mathematical modeling and artificial intelligence within smart food systems.

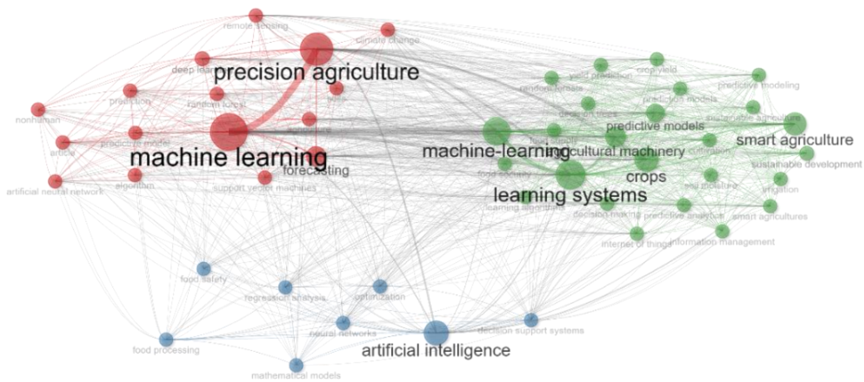

Figure 8. Co-occurrence Network

The results indicate that machine learning, artificial intelligence, and smart agriculture are the themes with the highest levels of connectivity within the research network. The prominence of these themes suggests that AI has become the core driver of smart food systems development and plays a critical role in a wide range of applications, including prediction, classification, monitoring, and data-driven decision-making.

In addition to the AI-centered clusters, the network also reveals the presence of themes related to predictive modeling, computational modeling, simulation, and optimization. The existence of these thematic groups demonstrates that mathematical modeling continues to play an essential role in explaining system dynamics, evaluating alternative scenarios, and identifying optimal solutions.

The strong connections among machine learning, predictive models, and computational modeling suggest that the distinction between data-driven and model-driven approaches is becoming increasingly blurred. These findings indicate that research is moving toward the integration of AI's predictive capabilities with the analytical strengths of mathematical modeling to support more intelligent and adaptive food systems.

Factorial Analysis

Factorial analysis using Multiple Correspondence Analysis (MCA) was conducted to identify the conceptual structure of the research field based on the relationships among keywords (Donthu et al., 2021). Unlike co-occurrence network analysis, which emphasizes direct relationships among themes, MCA enables the identification of research clusters that represent distinct conceptual paradigms. The results reveal the existence of two major groups that shape the development of research on mathematical modeling and artificial intelligence in smart food systems.

The first group is dominated by themes such as machine learning, artificial intelligence, deep learning, neural networks, remote sensing, and precision agriculture. This cluster represents the data driven paradigm, an approach that leverages large scale data to generate predictions, classifications, and automated decision recommendations.

The second group is characterized by themes such as mathematical modeling, optimization, simulation, computational modeling, and decision support systems. This cluster represents the model driven paradigm, which focuses on understanding system behavior, evaluating alternative scenarios, and identifying optimal solutions through mathematical models.

Interestingly, these two groups are not entirely separated but are connected through themes such as predictive modeling and resource optimization. This pattern indicates a growing convergence between data driven and model-driven approaches in the evolution of smart food systems.

These findings suggest that contemporary research no longer relies exclusively on either paradigm. Instead, the field is moving toward the integration of AI's data learning capabilities with the optimization and interpretability strengths of mathematical modeling. Consequently, the MCA results provide conceptual evidence that the future of smart food systems will increasingly be shaped by approaches that combine these two paradigms into a unified framework.

Toward Hybrid Intelligent Food Systems: A Conceptual Framework

The results of the various bibliometric analyses indicate that the development of smart food systems is no longer dominated by a single analytical approach. Instead, the field has evolved through the integration of the data driven paradigm, based on artificial intelligence, and the model driven paradigm, grounded in mathematical modeling.

The data-driven approach enables systems to learn patterns from large-scale datasets and generate accurate predictions through machine learning, deep learning, and sensor technologies (Ahmed et al., 2026). However, this approach often faces limitations in terms of interpretability and decision optimization. In contrast, the model driven approach offers advantages in simulation, optimization, and scenario evaluation, but it frequently relies on strong assumptions and may struggle to adapt to rapidly changing data environments (Kostić et al., 2026).

Based on these findings, this study proposes the concept of Hybrid Intelligent Food Systems, defined as systems that integrate the predictive capabilities of AI with the analytical and optimization strengths of mathematical modeling. Within this framework, AI functions as a learning engine that generates information and predictions, while mathematical modeling serves as a decision engine that determines optimal decisions based on those predictions. The integration of these two approaches enables the development of food systems that are more accurate, adaptive, transparent, and sustainable.

Future Research Agenda

Based on the results of the bibliometric analysis and the proposed conceptual framework, several promising directions for future research can be identified.

Table 1. Future Research Agenda in Smart Food System

Research Area	Current Status	Future Direction
Mathematical Optimization	Research remains largely reliant on conventional modeling approaches	Integration of AI and Optimization for Real Time Decision Making
Machine Learning	Studies are predominantly focused on prediction and classification tasks	Explainable AI and interpretable learning systems
Precision Agriculture	Research primarily emphasizes monitoring and predictive capabilities	Autonomous decision making systems
Food Processing	Applications are mainly concentrated on quality assessment	Intelligent process optimization
Supply Chain Management	Current developments focus on demand forecasting and distribution optimization	Adaptive supply chain optimization
Sustainability Assessment	Implementation and adoption remain relatively limited	AI-driven sustainability management
Resource Allocation	Decision making processes are primarily based on mathematical models	Hybrid AI based resource optimization
Decision Support Systems	Most systems operate under a semi-automated framework	Fully intelligent decision support systems

4. CONCLUSION

This study analyzed the global development of research on mathematical modeling and artificial intelligence in smart food systems using a bibliometric and science mapping approach based on Scopus data from 1994 to 2026. The results indicate that this research field has experienced rapid growth, particularly after 2020, as evidenced by the increasing number of publications related to machine learning, artificial intelligence, precision agriculture, predictive modeling, and smart agriculture.

The conceptual structure analysis revealed that the development of this field is shaped by two major paradigms: the data driven approach, which focuses on data based learning and prediction, and the model driven approach, which emphasizes optimization, simulation, and decision making through mathematical modeling. The factorial analysis further demonstrated that these two paradigms are becoming increasingly integrated through themes such as predictive modeling and resource optimization.

A key finding of this study is the growing convergence between AI and mathematical modeling in the development of smart food systems. Based on the synthesis of all analytical results, this study proposes the concept of Hybrid Intelligent Food Systems, defined as systems that integrate the predictive capabilities of AI with the optimization, simulation, and interpretability strengths of mathematical modeling to support more effective and sustainable decision making.

Future research should focus on developing hybrid approaches that combine machine learning, optimization, simulation, digital twins, and Explainable Artificial Intelligence (XAI) within a unified framework to support the next generation of smart food systems.

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