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Mapping the Intellectual Landscape of 3D Food Printing: A Bibliometric and Network Analysis

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Abstract

Although interest in additive manufacturing (AM) in the food sector has gained increasing attention in recent years, a comprehensive study combining bibliometric and network analyses to map the intellectual landscape of 3D food printing (3DFP) is still lacking. Data were collected utilizing the Scopus database from 2011 to 2024, encompassing a wide range of scientific publications. Key bibliometric indicators, including author influence, affiliation statistics, leading journals, keyword statistics, and three-field plots, were analyzed to highlight leading contributors and emerging themes. Co-citation, citation, and co-authorship network analyses were performed to clarify the collaborative framework and intellectual knowledge driving the advancement of the field. The findings show a steady growth in research output, with significant contributions from China, the USA, and India. Four major thematic clusters were identified i.e., pharmaceutical 3D printing, structured and bio-polymer based material used in 3D printing, the rheological and mechanical properties of food and biomaterials, and the design of edible food inks. The emerging trends for future research were found to be plant-based formulations, AI-assisted printing and sustainable food production for clinical nutrition and space applications. A roadmap for the future development of this emerging interdisciplinary field is provided, along with limitations and implications for further research. Overall, this study provides a thorough knowledge map of 3DFP research along with practical insights that researchers and industry stakeholders can use to strategically position future studies, promote cooperation, and expedite development and commercialization.

Keywords
Additive manufacturing, 3D printing, Food printing, Bibliometric analysis, Network analysis.

1. Introduction
The food supply chain is facing a major shift propelled by the growing demand for sustainability, quality, resource efficiency, consistency, and personalized nutrition. Conventional food processing faces many challenges regarding maintaining sustainable food production, adapting to new demands, customization, environmental impact, and delivering high-quality food products at the same time (Wang & Boh, 2012). Against this backdrop, 3D printing is a tremendous new approach with potential to redefine food design structure, production, and consumption paradigms. The driving forces in 3D food printing are the need for customization or personalization of foods, creating complex 3D-shaped foods, and precise nutrition control, along with other advantages of additive manufacturing (Holland et al., 2018; Lipton et al., 2015). Researchers began analyzing AM around the mid-2000s to test whether edible pastes like chocolate, dough, and cheese could be printed in customized shapes and structures. The increasing consumer demand and interest in personalized nutrition led the researchers to shift to additive manufacturing for food. The shift required integrating engineering, food processing, food science, and nutrition. Researchers at Cornell University's Computational Synthesis Lab developed one of the first open-source food 3D printers, which opened a door for the

design of edible foods. Their "Fab@Home" project exemplified printing with chocolate, cookie dough, and cheese pastes (Periard et al., 2007). The 3D printing concept emerged in 1977, but the first patent for 3D food printing appeared in 2001 (Escalante-Aburto et al., 2021). To date, most review articles published in the field of 3D food printing have emphasized on the food processing and technologies and process parameters such as nozzle diameter, layer height, infill density and pattern, printing width, material properties, texture, volume, object dimension, gel strength, glass transition temperature, rheological properties and mechanical properties(Pulatsu & Lin, 2021). Scholars' growing interest in printability, optimization of food ink formulas, material suitability for 3D printing, and supply chain resilience leads them to publish more articles on 3D printing (Ababou et al., 2023; Pulatsu & Lin, 2021). However, bibliometric analysis and network analysis on the application of 3D printing in the food industry are lacking. In this study, a bibliometric and network analysis is conducted on the application of additive manufacturing or 3D printing for the food industry. Bibliometric analysis is a popular method for exploring and analyzing large sets of scientific data systematically (Donthu et al., 2021). It shows how a topic has evolved and identifies which areas are emerging, stagnant, or declining. This paper aims to achieve the following objectives:

- To map global research networks to visualize the leading authors, journals, institutions, and the countries that collaborate the most in this field
- To identify research trends by analyzing keyword co-occurrence
- To develop a strategic roadmap to be used by researchers and the industrial actors that will help in coordinating future studies better and aligning with the research area

The advantage of using bibliometric analysis is to analyze a large number of contributions and to clearly identify the most relevant clusters of investigation, which permits to identification of the future trends of application of 3D printing in the Food industry (Scatto et al., 2025). It helps us to identify the influential work by revealing the most cited authors, journals, and papers, highlighting who shapes the field. Network analysis provides the capacity to estimate complex patterns of relationships, and the network structure can be analyzed to reveal core features of the network (Hevey, 2018). It maps research gaps in some areas that remain underexplored. Additionally, it guides future work and helps new researchers identify where they can contribute.

2. Methodology

This study uses a quantitative science mapping design that integrates descriptive bibliometrics with network analysis to chart the intellectual structure and evolution of 3DFP. The methodological process is schematically represented in Figure 1. The research paper was initiated by defining and searching with keywords related to 3DFP. The time range was taken from January 2011 to December 2024. The Scopus database was utilized for the collection of data due to its extensive coverage of trustworthy indexed journals, books, and conference proceedings in engineering and food science (Donthu et al., 2021). This ensures that the collected data is robust, authoritative, and relevant to the field under investigation. For the data collection, specific search keywords were combined *(Additive manufacturing OR 3d printing OR Rapid prototyping OR Additive fabrication OR Food fabrication OR Layered manufacturing OR Extrusion-based food printing OR Fused deposition modeling) AND (Food industry OR Food* OR Food processing OR Personalized nutrition).* After data collection, all records were screened for completeness and consistency, and missing values and duplicate entries were systematically identified and removed to ensure data integrity, improve data quality, enhance processing efficiency, and ensure accuracy. The analysis of articles consists of various bibliometric and network analyses, which are discussed in detail in the data analysis and findings. The bibliometric analysis phase involved a quantitative assessment of the literature to map the intellectual landscape of the field. Key statistics were extracted, including the most influential authors, journals, countries, and institutions, as well as top keywords statistics, and three field plots. Network analysis was performed to reveal the structural connections within the research domain, specifically focusing on citation analysis, co-citation analysis, and co-authorship network analysis. The statistical and visualization analyses were conducted using two specialized software VOSviewer and Biblioshiny. The search results were exported in CSV format to facilitate analysis using these softwares. Specifically, descriptive bibliometric metrics were generated using the Biblioshiny application, a web-based graphical user interface for the R-package 'bibliometrix' and the structural and relational mapping was performed using VOSviewer (Version 1.6.20). The final stage of the analysis involved synthesizing the quantitative outputs from the bibliometric tools into meaningful research conclusions. Thematic and trend analysis is the stage that connects statistical findings with academic interpretation.

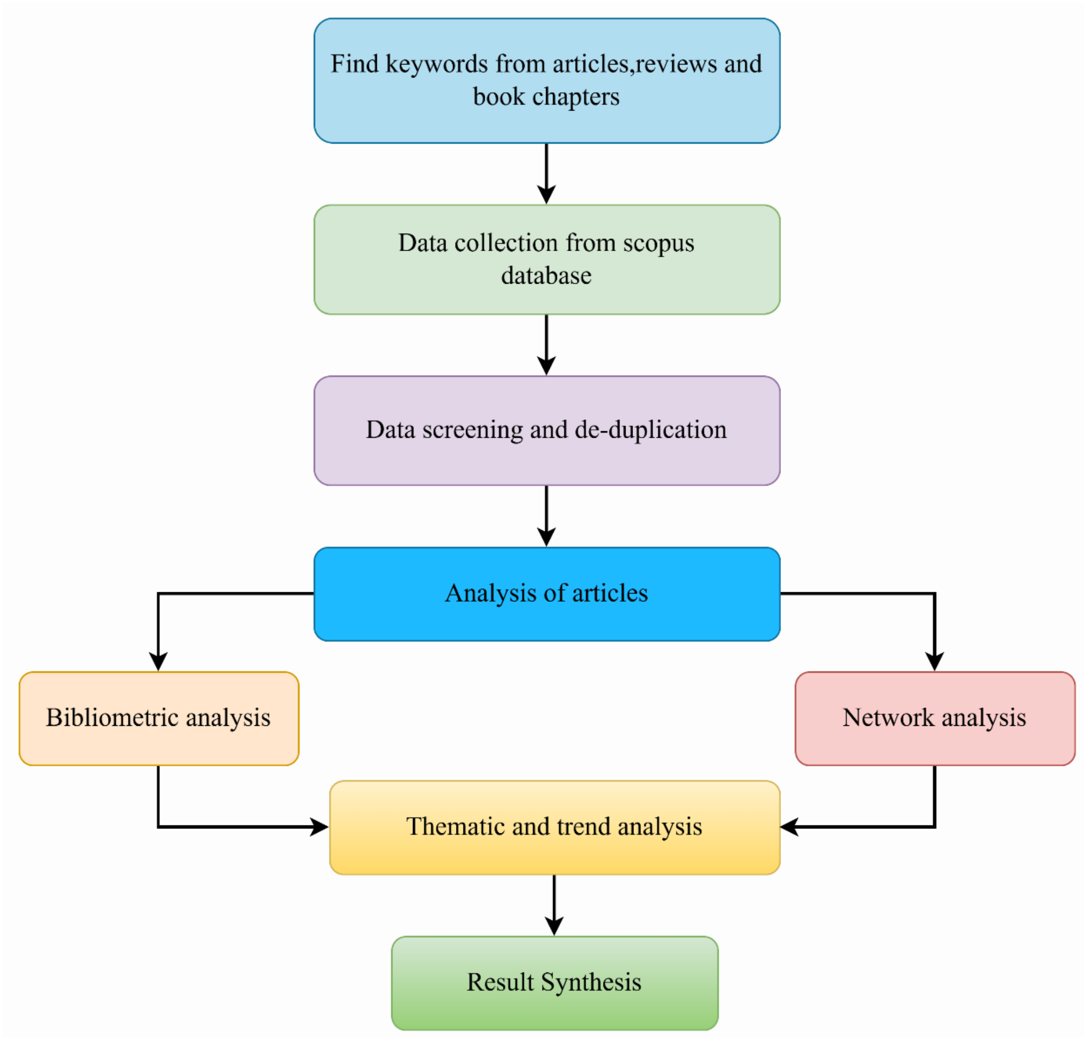

Figure 1. Research Methodology Steps

3. Data Analysis and Findings

In this study, the two primary stages of data analyses were bibliometric analysis and network analysis. The bibliometric analysis outlined the general direction of the field by methodically examining a large corpus of research papers using quantitative tools. After that, network analysis was used to find hidden structures and deeper relationships in the field. Together, these analyses offer a comprehensive picture of the state of the field and point to promising opportunities for further research and cooperation. These two strategies provide a thorough picture to connect research findings with qualitative relationships and field dynamics.

3.1 Bibliometric Analysis

Bibliometric analysis represents the first stage of this study, preceding the network analysis. Author influence, affiliation statistics, keyword statistics, top influential journals, and three-field plots are among the important analyses carried out. The specialized software tools like Tableau, Microsoft Excel, and Bibliometrix (RStudio) were used in these analyses because of their ability to manage sizable datasets and produce perceptive visualizations that improve comprehension of the research environment.

3.1.1 Author Influence

In order to assess the author's influence in the field of 3DFP research, an analysis was carried out based on the total number of publications per author. The author's publication frequency was calculated using the Biblioshiny interface in R, following the retrieval of bibliographic records from the Scopus database. After that, the authors' rankings were determined and arranged according to the volume of their publications in descending order. Table 1 lists the top ten contributing authors along with the number of publications they have authored. According to the analysis, M. Zhang was the most prominent with the highest number of publications (96). He was followed by B.R. Bhandari (56) and S. Prakash (35), the next most prolific authors. This concentration highlights the important contribution and fundamental role that these important researchers have played in developing the field of 3DFP.

Table 1. Top Ten contributing authors

Author Name	**No of Publications**
M. Zhang	96
BR Bhandari	56
S Prakash	35
HJ Park	33
Arun S. Mujumdar	32
JA Moses	28
HW Kim	26
C. Anandharamakrishnan	23
DJ McClements	19
Z Liu	16

3.1.2 Affiliation Statistics

To determine the geographical origins of the publications of the corresponding authors analysis was carried out using the Biblioshiny tool. Table 2 lists the top ten contributing countries according to the total frequency of their publications. The analysis shows that China is the top contributor, having published a noteworthy 1,515 articles. Notably, this amount is more than twice as much as the 674 articles from the United States, which ranks as the second-highest contributor. India ranks the third position with 609 contributions. This large gap highlights the strength of China's position in the research domain. This outstanding output demonstrates a significant, sustained institutional commitment to this field of study. In addition, the results from India and the United States support their positions as major international R&D hubs.

Table 3 presents the top ten institutional contributors to 3DFP based on total articles published from 2011 to 2024. Among the listed institutions, five of them are located in China, Jiangnan University leads with 494 publications. This further confirms that China is a key active country in this area and accounts for almost 63% of the total. China, USA, India and Singapore are the most productive contributors as a result of their leading organizations. This data helps 3DFP researchers find partners and study opportunities.

Later, the data table was imported into Tableau software to visualize and analyze the distribution of contributing countries. The data table listed each country's publication count, which was used to adjust the size of the circles. Figure 2 represents the geographic overview of contributing countries. The circles on the map show each country's publication frequency in this field. Larger circles indicate higher publication counts and so greater research output from those countries (China, United States, and India). Overall, it highlights the global interest, involvement and collaboration in 3DFP research.

Table 2. Top 10 contributing countries

Country	Publication Frequency
China	1515
United States	674
India	609
Singapore	277
United Kingdom	219
Australia	186
Spain	164
Canada	146
Brazil	142
France	142

Table 3. Top 10 contributing organizations

Organization	No of Publications
Jiangnan University	494
Dalian Polytechnic University	187
Southwest University	139
The University of Queensland	124
Korea University	115
National Institute of Food Technology	108
China Agricultural University	104
Wageningen University and Research	93
National University of Singapore	82
Shaanxi University of Science and Technology	81

Figure 2**.** Geographical locations of contributing countries

3.1.3 Keywords Statistics

A keyword analysis was conducted to identify the most prominent topics and research trends in the field of 3DFP. Using Biblioshiny (RStudio) tool, the keywords were extracted from the dataset during 2011 to 2024. Table 4 presents the top ten keyword occurrences. The analysis shows that 3d printing (3920 occurrences) is the most frequent keyword, which clearly indicates the centrality of this technology in recent research. 3D food printing (827 occurrences) and additive manufacturing (567 occurrences) also show high prevalence, highlighting the integration of advanced fabrication techniques with food science. A strong interest in studying material behavior and food composition in this area is indicated by the strength of the keywords, e.g., rheology (523 occurrences), starch (329), and textures (205). The overall view of the scientific landscape offered by the keyword frequency distribution makes it possible to identify both new and emerging domains in the field of 3DFP as well as established thematic areas.

Table 4. Top 10 keywords

Keywords	Frequency
3d printing	3920
3d food printing	827
Additive manufacturing	567
Rheology	523
Human	427
Food	414
Starch	329
Article	274

Chemistry	206
Textures	205

3.1.4 Top Influential Journals

Table 5 represents the top ten journals that have contributed most to 3DFP research between 2011 and 2024. The Food Hydrocolloids (132 documents) and Journal of Food Engineering (102 documents) have the highest publication frequency. A higher publication count suggests that the journal is actively involved in the field and that it is a key source of publications in the area of 3DFP. Food Hydrocolloids focuses on the formulation and rheology of hydrocolloid-based food materials, while the Journal of Food Engineering emphasizes process design and optimization that support advancements in 3DFP. Beyond the leading journals, other significant publications include Foods (57 documents), the International Journal of Biological Macromolecules (56 documents), and Food Research International (43 documents). Overall, the field lies at the cross-section of materials science, biopolymer research, and food engineering and in which the combined knowledge of these fields leads to continuous developments in printable formulation, fabrication processes, and product design.

Table 5. Top ten contributing journals

Journals	Documents
Food hydrocolloids	132
Journal of food engineering	102
Foods	57
International journal of biological macromolecules	56
Food research international	43
Food chemistry	37
LWT	34
Innovative food science and emerging technologies	32
Trends in food science and technology	26
Food and bioprocess technology	25

3.1.5 Three-Field Plots

A three-field plot analysis is used to examine the relationships between author countries, research topics and publication sources in the field of 3DFP (Aria & Cuccurullo, 2017).

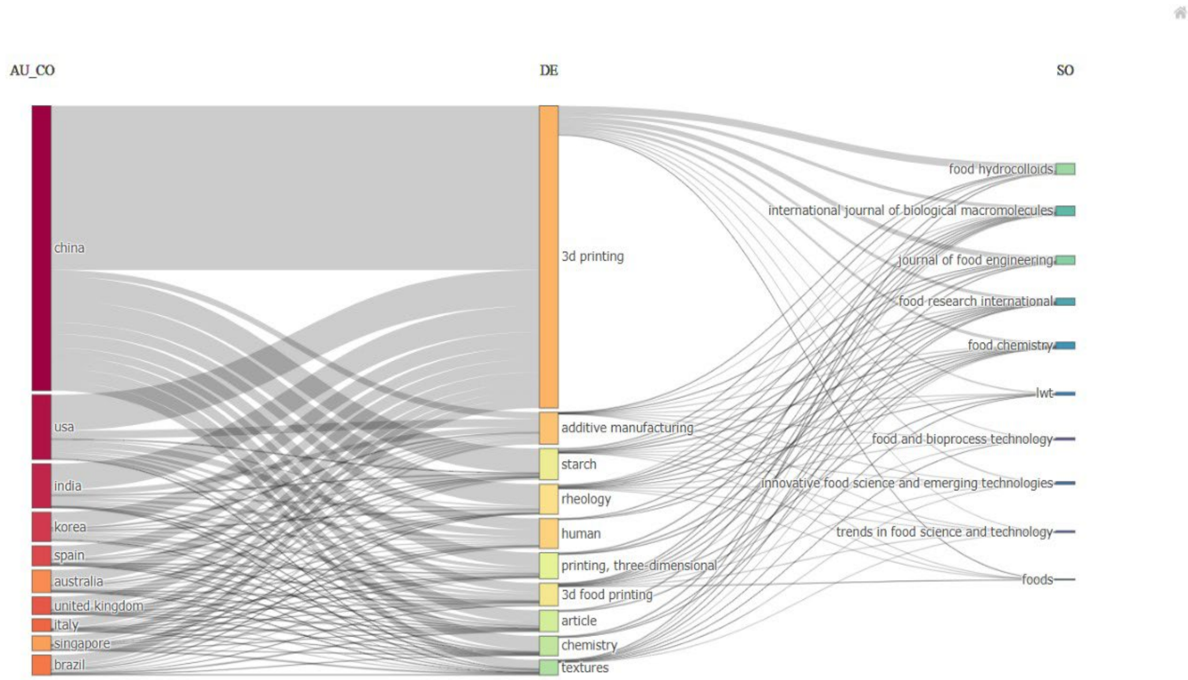

Figure 3. Three-field plot diagram author countries (AU_CO), document keywords (DE), sources (SO)

This diagram visualizes how research output flows from leading countries (left field) through major keywords (middle field) to the main publication sources (right field). The thickness of the connecting lines indicates the strength of association, representing the number of publications linking one element to another. The analysis clearly shows that China is the most dominant contributing country by a significant margin, followed by the USA and India. The central research theme bridging these countries is "3D printing," which forms the largest node in the diagram. Other prominent topics include additive manufacturing, rheology, starch, and 3D food printing, reflecting both the material science and technical areas. As seen in Figure 3, most studies on 3D printing have been published in Food Hydrocolloids, International Journal of Biological Macromolecules, and Journal of Food Engineering. In addition, most of the 3DFP articles are related to Food Chemistry, LWT, Food and Bioprocess Technology, and Innovative Food Science and Emerging Technologies.

3.2 Network Analysis

Network analysis is the mathematical study of systems, which consists of nodes (elements) and edges (connections) and it focuses on the network's topology and how a structure governs flows, dynamics and functions of the systems (Newman, 2003).Also, the relationships between authors, institutions, keywords, or documents can be visualized and analyzed using VOSviewer. In this study, to conduct a network analysis, a set of interconnected objects for a specific domain is required (Bellomi & Bonato, n.d.). In this study, co-citation analysis, keyword co-occurrence analysis, co-authorship network analysis, and citation analysis were conducted on data from Scopus.

3.2.1 Co-citation Analysis

Co-citation analysis is a method for identifying key research themes and clusters for related research fields(Chen et al., 2010). It helps to detect influential papers or authors. It is also used to understand the evolution or trend of research topics. It can map the conceptual structure of scientific data. We can see four clusters in Figure 4, which are labeled in Table 6 according to the main themes of the clusters.

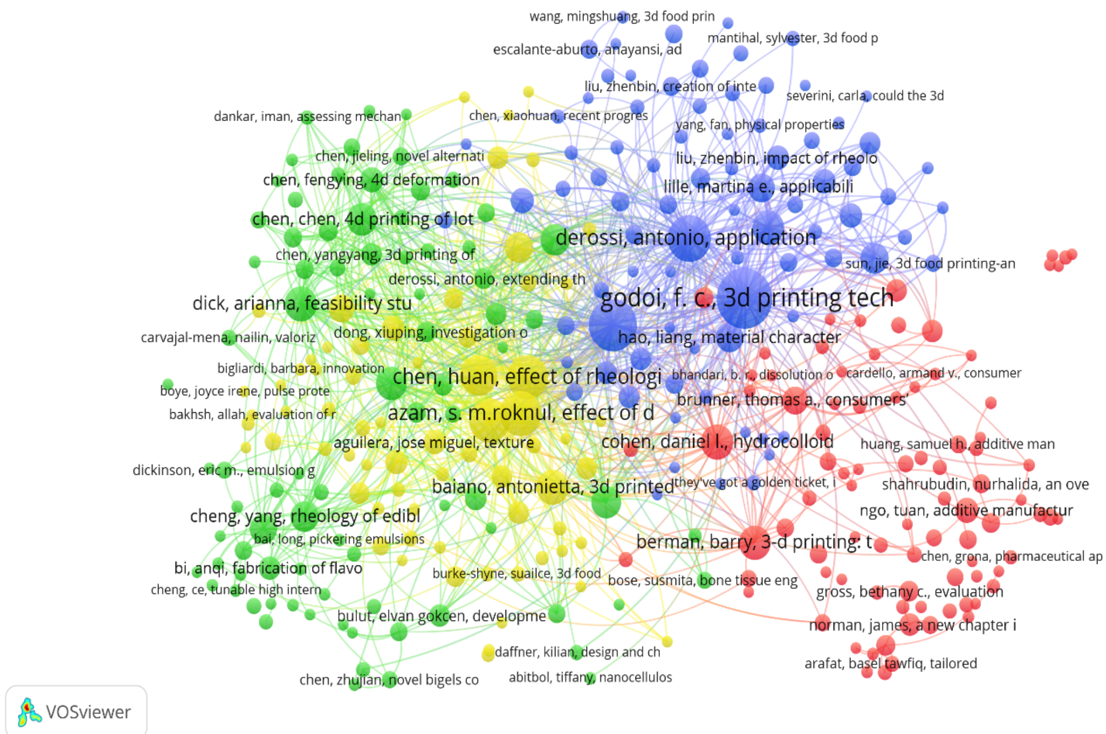

Figure 4. Co-citation network analysis

Table 6. Co-citation clusters with their main themes and label

Cluster	Items	Main Themes	Cluster label
Cluster-1 (Red)	86	Advancement of technologies in AM and FDP (Fused Deposition Modeling), SLS(Selective laser Sintering) applications in pharmaceutical 3D printing.	Pharmaceutical 3D Printing
Cluster-2 (Green)	83	Structuring and engineering of rheological properties (such as edible oleogels), emulsions,bigels, nano cellulose-based systems and material characteristics, use of biopolymers and hydrocolloids in applications of 3D printing, food design, and controlled drug delivery.	Structured and biopolymer-based materials (gels, emulsions, oils) for 3D printing.
Cluster-3 (Blue)	83	Analysis of pasting, gelation, and rheological properties and use of different materials (corn, gel, paste, starch, etc) and mentioned properties in additive manufacturing.	Rheological properties of food and biomaterials in 3D printing.
Cluster-4 (Yellow)	69	Rheological characterization of food materials (gums, flours, biomass, protein, etc), Direct Ink Write (DIW), Edible ink design for nutrients-enriched food (such as vitamin D), texture-modified food, alternative protein and biomass-based foods etc.	Edible food ink design for extrusion-based 3D printing or printability

Cluster 1: Pharmaceutical 3D printing

The pharmaceutical industry joined the fourth industrial revolution with the 3D printing of medicines (Araújo et al., 2019). Various 3D printing methods exist, which use thermal and method-based mechanisms. Among these techniques, Fused Deposition Modelling (FDM) has obtained substantial interest within different fields, including pharmaceuticals, food technology, and tissue engineering. In drug formulation, FDM shows strong potential for personalized oral medicine, which simplifies treatment and produces a personalized dosage form. Fused deposition modelling can enable digital pharmacies and personalized medicine. Polymer blends were used to improve printability and drug release control of 3D printed dosage forms (Alhijjaj et al., 2016). The preparation of dosage forms with complex designs and geometries, multiple actives, and tailored release profiles helped to fulfil the real potential of 3D printing in the pharmaceutical industry (Alhnan et al., 2016).

Selective Laser Sintering (SLS) technology is capable of fabricating orally disintegrating tablets (ODTs) (Fina et al., 2018). SLS is a one-step fabrication process involving a laser to selectively sinter powder particles in a layered manner to form 3D structures. The SLS (Selective Laser Sintering) fabrication of pharmaceutical powder formulations incorporating drug entities was conducted, and subsequently, the mechanical integrity, disintegration properties and drug elution kinetics were thoroughly assessed. Orally disintegrating films (ODFs) have been effectively engineered to demonstrate a rapid disintegration period of under 15 seconds, thereby guaranteeing the stability of the active pharmaceutical ingredient (API) and accuracy in dosage formulation. Taken together, these academic contributions articulate 3D printing as a groundbreaking framework for the manufacture of pharmaceutical products.

Cluster 2: Structured and biopolymer-based materials (gels, emulsion, oil) for 3D printing

Recent studies have revealed substantial advancements in the formulation and structuring of intricate materials such as oleogels, bigels, emulsions, and bio-derived scaffolds for applications in the food and pharmaceutical sectors. Food blends with similar rheological, moisture, and textural properties could be used as “ink” for an extrusion-based 3D food printing(Azam et al., 2018). Fish gelatin gum arabic complexation helped to enhance emulsion properties by refining viscoelastic, LAOS, and tribological behaviors. Greater fish gelatin gum arabic complexation at lower pH resulted in higher monodispersity in oil droplet size distribution and increased network extensibility.(Anvari & Joyner (Melito), 2018). This finding can be used to develop emulsion-based food products with greater stability and specific textural attributes. EC2%/AA4% oleogel is found as a healthier alternative to hydrogenated shortening and animal fats (Adili et al., 2020). The innovation of reinforced ethyl cellulose–based oleogels incorporating adipic acid exhibited enhanced mechanical stability and demonstrated potential as a fat substitute in baked goods and meat products, and these findings facilitated healthier and better formulations. The development of reinforced ethyl cellulose–based oleogels incorporating adipic acid has demonstrated significantly improved mechanical stability and exhibited substantial promise as a fat substitute in baked goods and meat products, thereby facilitating the formulation of healthier and superior alternatives.

Cluster 3: Rheological properties of food and biomaterials in 3D printing

This cluster examines the rheological behavior and structural dynamics of soft, viscoelastic materials, whether food pastes, starch gels, hydrogels, or dense colloidal inks, and how these behaviors affect extrusion-based and 3D printing and the functionality (texture, stability, or biological performance) of these materials and their characteristics. These papers revolve around the same fundamental problem, which is to understand and control viscoelastic flow and structure formation in complex systems. Rheological control is a crucial part of successful extrusion or texture formation. Guar gum and xanthan gum modify the pasting and rheological behavior of native and anionic tapioca starches. Gum type and starch modification influence viscosity, gel strength and texture (Chaisawang & Suphantharika, 2006). Many authors found that the distribution of water could affect the rheology and then the machinability of dough. Nuclear Magnetic Resonance (NMR) demonstrates the sequential transformations of water from a free state to a bound state and subsequently to an immobilized state (Assifaoui et al., 2006). The rheological behaviour of dense colloidal pastes is used extensively in 3D printing. The dense colloidal pastes have viscoelastic and yield stress properties which influence shape stability, printability, and extrusion during the printing process (Avery et al., 2014).

Cluster 4: Edible food ink design for extrusion-based 3D printing or printability

This cluster represents how food ink design affects extrusion-based 3D printing or printability. Cellulose nanofibrils (CNCs) act as an effective rheological additive which promotes shear-thinning and viscosity in the studied edible feedstocks for DIW 3D printing of edible structures (Armstrong et al., 2022). The addition of rice flour improved the textural and rheological properties of the printing material supply that aids in the printing process. Both EY (egg yolk) and EW (egg white) in their natural form are not printable. But EY and EW combined with rice flour (starch) form a smooth paste possessing pseudoplastic behaviour that makes the material suitable for printing (Anukiruthika et al., 2020). Rising demand for the utilization of plant-based proteins as a substitute for those of animal origin in food formulations shows that the rheological properties of commercial pea (PPI) and soy protein isolates (SPI) pastes were extensively affected by protein concentration. Protein concentrations from 14% to 21% *w*/ w were associated with the printability regarding extrusion-based 3D printing (Ainis et al., 2023). Layered food structure based on 3D printing significantly influences the microstructure and moisture content of gluten-free snacks (Agarwal et al., 2022).

3.2.2 Keyword Co-occurrence Analysis

Keywords co-occurrence network analysis is a type of analysis where keywords are represented as nodes and the co-occurrence of keywords is represented as the link between the nodes (Ozek et al., 2022). Using author keywords in co-occurrence analysis indicates that the analysis is based on the keywords provided by the paper's authors themselves. To conduct co-occurrence analysis, VOSviewer, a visualization tool, is used. The node represents a keyword, and the size of the nodes indicates the keyword frequencies in VOSviewer (Bhowmik et al., 2024). From Figure 5, we can see that the keyword 3D printing has the biggest node size, indicating that this keyword appeared more frequently and was more prominent in literature. The distance between two nodes is approximately inversely proportional to their similarity (relatedness in terms of co-occurrence). This means that keywords with a higher rate of co-occurrence remain closer to each other (Bornmann et al., 2018). 3d printing and additive manufacturing are the most frequently used items according to the output of our analysis. The total link strength indicates how vigorously a keyword is connected to all other items or keywords combined. 3D printing has the highest total link strength among the items.

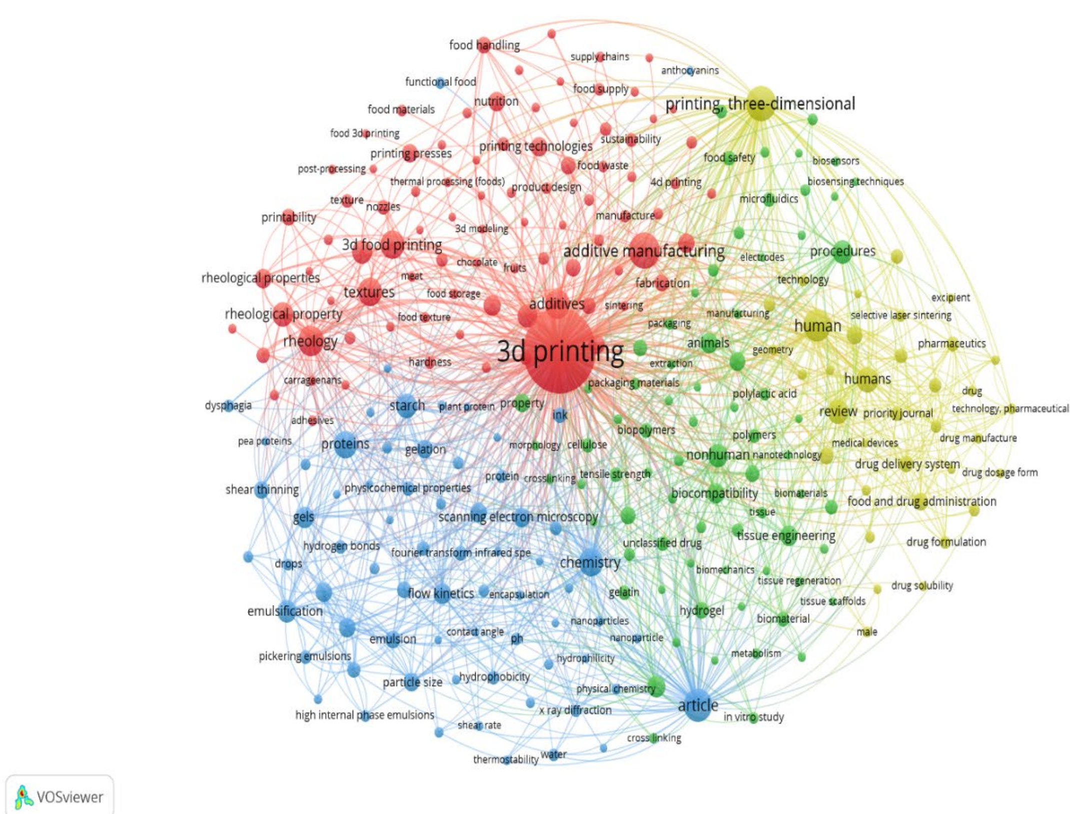

Figure 5. Keyword co-occurrence analysis

3.2.3 Co-authorship Network Analysis

Co-authorship network analysis is a powerful tool for visualizing and understanding the collaborative dynamics among researchers, organizations, and countries by revealing the cooperation structure and information about the core position within the network (Fonseca et al., 2016). It studies the collaboration patterns among researchers based on the papers they have written together or combined. Co-authorship analysis was carried out in this study utilizing

VOSviewer, with a threshold value of 5 established for the number of documents authored by a given individual. Among 8068 authors in total, 178 met the criterion. From Figure 6, we can see that the co-authorship network delineated in our analysis comprises four distinct clusters. Each cluster signifies a collective of authors or researchers who engage in frequent collaborative endeavors. Authors who collaborate frequently are grouped in the same color. The larger node generally indicates higher centrality or more connections of the author in the network.

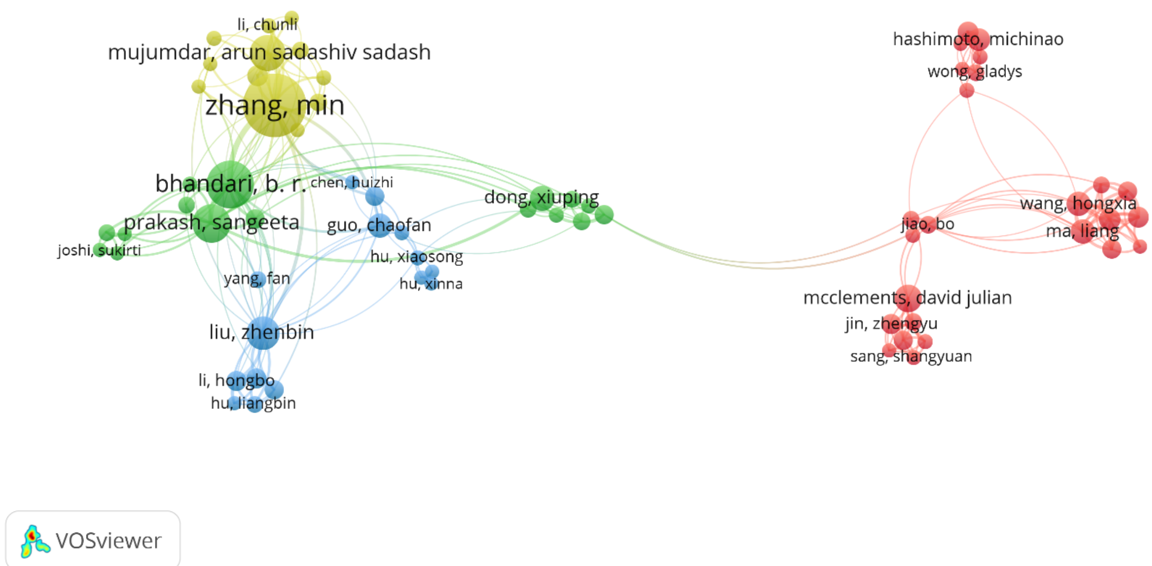

Figure 6. Co-authorship network analysis.

3.2.4 Citation Analysis

The popularity of an article can be measured using a simple method that counts the number of citations. Citation counts play a dominant role in assessing the impact of researchers, journals, institutions, domains, and countries (Yan & Ding, 2010). Citation analysis is done mainly to measure research impact, identify influential works and authors, and to discover research trends and topics. Citation analysis usually does not take the quality of citations into account(Ding & Cronin, 2011). It helps to reduce bias by focusing only on the influential works. It also helps to find out the most relevant and impactful studies in a specific field. In this analysis, we have listed the top-cited documents of authors. Here, the citation number indicates the number of times the documents have been cited by other documents in our dataset. From Table 7, we can see Ligon (2017) has 3091 citations, which means this is the most cited paper. It implies that this document is the foundational study in our dataset. The top 10 cited papers range from 2014 to 2019. Highly cited papers are usually considered influential.

Table 7. Top 10 most cited papers.

Document	Citation
Ligon(2017)	3091
Lee ventola(2014)	1370
Eckel(2016)	998
Klerkx(2019)	919
Saadi(2022)	870
Godoi(2016)	805

Bandopadhyay(2018)	803
Liu(2017)	693
Ye(2018)	613
Yang(2017)	553

4. Future Trends

The future trends in bibliometric and network analysis for 3DFP are likely to focus on greater collaboration, real-time data integration, and more detailed mapping of influence and emerging themes. 3DFP is coming into a new era of smart manufacturing and interdisciplinary growth. The next phase of growth will be driven by the combination of AI assisted design, advanced edible materials, and sustainability-focused innovations. This progress will be supported by increased collaboration among experts in these fields (food science, materials, and data technology). Future technological advances will focus on using artificial intelligence (AI) and machine learning to optimize printing settings and ink formulations in real time. Research suggests that predictive modeling can improve extrusion stability and print accuracy, leading to adaptive printing systems capable of self-correcting during operation (Ma et al., 2023). Additionally, closed-loop feedback control made possible by the integration of sophisticated sensors into 3D printers will aid in preserving the structural integrity and uniformity of food texture throughout the printing process (Wang et al., 2025). The creation of edible inks using biopolymers and plant-based ingredients is another significant trend. To develop inks that are suitable for 3D printing while having a minimal negative impact on the environment, researchers concentrate on using renewable resources like algae, legume proteins, and powders made from food waste. This method aids in the transition to circular food systems and the worldwide movement for nutrient-dense, sustainable diets (Zhong et al., 2023). Further, 4D food printing gives 3D-printed foods a temporal dimension. This implies that after printing, the food can alter its flavor, texture, or shape in response to stimuli like heat, moisture, or pH variations, resulting in dynamic and engaging eating experiences. Furthermore, it is still crucial to incorporate social and regulatory aspects into 3D-printed foods. Responsible development and commercialization depend on addressing ethical issues, comprehending consumer perceptions, and guaranteeing food safety (Baiano, 2022). The next crucial research frontier will be defined by the shift from proof of concept and lab prototypes to industrial pilot implementations. All things considered, combining technological innovation with cooperative, data-driven research will be essential to the future development in this field. 3DFP will be able to transition from experimental novelty to a revolutionary pillar of future food manufacturing by tying AI, sustainable materials and human nutrition together.

5. Conclusion and Implications

3DFP is a new technology that uses digital designs to create layered food construction that creates sustainable, nutrient-dense and customized goods. To create cutting-edge food products, this research combines materials engineering, food science and 3D printing methods. In-depth bibliometric and network analysis are presented in this study to map the global 3DFP research landscape. In order to transform 3DFP from a specialized innovation to a promising technology with a wide range of applications, the findings highlight the primary contributors, significant research trends and cooperative networks. Researchers, business executives and legislators can use the overview's insightful strategic recommendations to guide future studies, technological advancements, and extensive commercialization in the 3DFP space. The study's limitations include its duration and dependence on the Scopus database, but the body of evidence it produced is solid. It creates a solid baseline for tracking upcoming shifts in the field's collaborative frameworks and research topics.

5.1 Theoretical Implication

Theoretical implications of the study are in the fact that the network-based and bibliometric data allow to explain the fundamental conceptual clusters of the 3DFP research effect, enhances the intellectual framework and locates 3DFP within the framework of the additive manufacturing food engineering and innovation research(Elshaer et al., 2024). Pharmaceutical printing, biopolymers and structured materials, printability-related rheology and edible-ink formulation are the primary areas of expertise for 3DFP. The conceptual underpinnings of 3DFP are described in this study. It gives researchers a coherent framework for developing research questions, choosing suitable methodologies and adding to the body of knowledge in the fields of digital manufacturing, materials engineering and food science. Methodologically, the integration of Biblioshiny (bibliometrix) with VOSviewer shows the use of network mapping and descriptive indicators to track topic evolution, identify research bursts and identify influential authors, institutions and journals. This method can be applied to related fields such as 4D food printing and alternative proteins.

5.2 Practical Implication

From a practical point of view, the findings indicate high-impact prospects for R&D and startups, such as AI-assisted printability control, plant-based and recycled inks, formulations that target texture and automated, scalable printing lines. Furthermore, the benchmark list of top contributors can guide collaborative activities and people recruitment. The results support the use of shared testbeds, interdisciplinary curriculums and standardized rules regarding materials, safety, labeling and hygiene in educational settings and policies, and help to tame the adoption risks. 3DFP can support inclusive and sustainable nutrition on a societal level by enabling customized diets, appreciating by products and reducing waste through on demand production. Future research will be more practically relevant if it is in line with consumer acceptance criteria and sustainability measures. To accelerate robust AI models and reproducibility, the field should strategically establish cross-regional research, conduct pilots in commercial kitchens and hospitals to validate cost and quality and create open benchmarks connecting texture, printability and rheology.

Conflict of Interest

The authors declare no financial or personal interests that may have influenced the work presented in this study.

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Data availability statement

No data associated with the study has been deposited into a publicly available repository. The authors confirm that the data supporting the findings of this study are available within the article.

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