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MAPPING THE SCIENTIFIC LANDSCAPE OF PERSONALIZED NUTRITION: DIGITAL HEALTH, AI-DRIVEN DIETARY SYSTEMS, AND RESEARCH INFRASTRUCTURES

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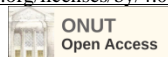
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Abstract. Personalized nutrition has emerged as one of the most rapidly developing areas of contemporary nutritional and biomedical science, reflecting a broader transition from generalized dietary recommendations toward individualized and data-driven health interventions. Over the last decade, significant advances in nutrigenomics, microbiome research, metabolomics, and digital health technologies have substantially transformed the scientific landscape of nutrition studies. At the same time, the growing implementation of wearable biosensors, continuous glucose monitoring systems, mobile health applications, and artificial intelligence-based dietary recommendation tools has accelerated the integration of precision nutrition into clinical and preventive healthcare practices. In parallel, research infrastructures and FAIR (Findable, Accessible, Interoperable, and Reusable) data principles have become increasingly important for ensuring interoperability, standardization, and large-scale exchange of biomedical and nutritional data. The aim of this study was to examine the global evolution of personalized nutrition research between 2015 and 2025 through a comprehensive bibliometric and science mapping analysis. Data were retrieved from the Scopus and Web of Science databases and analyzed using bibliometric indicators, co-authorship networks, keyword co-occurrence analysis, citation mapping, and thematic clustering techniques. Visualization and mapping of scientific trends were performed using VOSviewer tools. The findings demonstrate a substantial increase in publication output and international collaboration in the field of personalized nutrition, particularly after 2020. The results reveal the emergence of several dominant thematic clusters associated with microbiome-based nutrition, AI-assisted dietary systems, mobile monitoring technologies, digital biomarkers, and precision metabolic assessment. The study also identifies leading countries, institutions, authors, and journals shaping the current scientific agenda. Furthermore, the analysis highlights the growing role of research infrastructures, biobanking ecosystems, and FAIR-oriented data management frameworks in supporting interdisciplinary and data-intensive nutrition research. The study contributes to a better understanding of the intellectual structure and technological transformation of personalized nutrition research and provides insights into future directions related to digital health ecosystems, predictive healthcare models, and infrastructure-enabled precision nutrition.

Keywords: personalized nutrition; bibliometric analysis; digital health; wearable devices; research infrastructures; FAIR data; mobile health applications..

Introduction. Formulation of the problem

Over the past decade, nutrition science has undergone a substantial transformation driven by

advances in biomedical research, digital technologies, and data-intensive healthcare approaches. Traditional dietary guidelines based on generalized population recommendations are increasingly being replaced by

precision and personalized nutrition models that account for individual biological, genetic, metabolic, and lifestyle differences. This transition reflects a broader shift toward preventive and patient-centered healthcare aimed at improving long-term health outcomes and reducing the burden of chronic non-communicable diseases.

The growing prevalence of obesity, type 2 diabetes, cardiovascular diseases, metabolic syndrome, and other nutrition-related disorders has intensified scientific interest in individualized nutritional interventions. Conventional dietary strategies often fail to consider interindividual variability in metabolic responses, nutrient absorption, genetic predisposition, and gut microbiota composition. As a result, contemporary nutrition research increasingly focuses on developing targeted dietary approaches capable of addressing the specific physiological and metabolic characteristics of individuals.

In this context, nutrigenomics has emerged as one of the key directions of modern nutrition science. The field examines the interaction between nutrients and genetic mechanisms, contributing to a better understanding of how dietary factors influence gene expression and metabolic pathways. Parallel advances in microbiome research have further demonstrated the critical role of gut microbial communities in regulating immune function, metabolism, neurological processes, and overall human health. These findings have stimulated the development of microbiome-based nutrition strategies aimed at optimizing dietary recommendations according to individual microbial profiles.

At the same time, the rapid digital transformation of healthcare systems has significantly expanded the technological capabilities of personalized nutrition research and practice. The widespread adoption of wearable biosensors, continuous glucose monitoring systems, smart health devices, and mobile health applications has enabled the real-time collection of physiological and behavioral data related to nutrition and metabolism. Such technologies support continuous monitoring of dietary habits, physical activity, glycemic responses, and other health indicators, thereby facilitating more adaptive and individualized nutritional interventions.

Recent developments in artificial intelligence and machine learning have further accelerated the evolution of precision nutrition. AI-assisted dietary recommendation systems are increasingly applied for predictive analytics, dietary pattern recognition, metabolic risk assessment, and personalized meal planning. These approaches rely on the integration of heterogeneous datasets, including genomic, metabolomic, microbiome, and lifestyle information, allowing for more accurate prediction of individual responses to specific dietary interventions.

Another emerging concept attracting growing scientific attention is the implementation of digital twins

in healthcare and nutrition science. Digital twins represent virtual models of individuals created through the integration of real-time biomedical, physiological, and behavioral data. In the context of personalized nutrition, such systems may support predictive simulations of metabolic responses, optimization of dietary strategies, and early prevention of nutrition-related diseases.

Collectively, these developments indicate that personalized nutrition is evolving into a highly interdisciplinary research domain situated at the intersection of nutritional science, biomedical informatics, artificial intelligence, mobile health technologies, and data-driven healthcare systems. This transformation has also increased the importance of large-scale biomedical data infrastructures, interoperability frameworks, and international research collaboration necessary for the effective implementation of precision nutrition approaches in clinical and public health practice.

The rapid advancement of digital technologies has fundamentally transformed the methodological and practical foundations of contemporary nutrition science. Traditional dietetics, which historically relied on standardized dietary guidelines and self-reported nutritional assessments, is increasingly being supplemented by data-driven approaches capable of generating continuous, individualized, and real-time health information. This technological transition has contributed to the emergence of precision nutrition models that integrate physiological monitoring, behavioral analytics, and predictive computational tools into nutritional assessment and intervention strategies.

One of the most significant developments in this area is the growing application of wearable biosensors in health and nutrition monitoring. Wearable technologies, including smartwatches, fitness trackers, biosensing patches, and integrated physiological monitoring devices, enable continuous collection of biometric data related to physical activity, heart rate variability, sleep quality, energy expenditure, and metabolic responses. Such technologies provide opportunities for dynamic assessment of lifestyle factors influencing nutritional status and facilitate the development of personalized dietary recommendations based on real-time physiological indicators.

Among the most influential innovations in recent years is the widespread implementation of continuous glucose monitoring (CGM) systems. Originally developed for diabetes management, CGM technologies are increasingly applied in personalized nutrition research to evaluate individual glycemic responses to specific foods and dietary patterns. Evidence from recent studies suggests that metabolic responses to identical meals may vary substantially among individuals due to differences in genetics, microbiome composition, physical activity, stress levels, and other physiological factors. Continuous glucose monitoring therefore represents an important tool for understanding

metabolic individuality and improving the precision of dietary interventions.

In parallel, mobile food tracking applications have become an integral component of modern nutrition management systems. Smartphone-based dietary platforms allow users to record food intake, monitor nutrient consumption, estimate caloric balance, and receive personalized nutritional feedback. Advanced applications increasingly incorporate artificial intelligence algorithms, image recognition systems, barcode scanning technologies, and behavioral analytics to improve dietary assessment accuracy and user engagement. The integration of mobile technologies into nutritional practice has also expanded opportunities for long-term dietary monitoring outside clinical settings.

These technological developments have contributed to the formation of smart nutrition ecosystems, which combine interconnected digital platforms, wearable devices, cloud-based databases, and predictive analytical tools into integrated health management systems. Smart nutrition ecosystems facilitate multidimensional analysis of dietary behavior, metabolic indicators, environmental influences, and lifestyle factors. Such systems are increasingly designed to support preventive healthcare strategies by enabling early identification of nutritional risks and adaptive modification of dietary recommendations based on continuously updated data streams.

Another important direction of technological transformation is the expansion of remote patient monitoring in nutritional and metabolic healthcare. Remote monitoring technologies enable healthcare professionals to supervise patients' nutritional status, metabolic parameters, treatment adherence, and lifestyle changes without requiring continuous in-person consultations. This approach has become particularly relevant in the context of telemedicine, chronic disease management, aging populations, and healthcare accessibility challenges. The integration of nutrition monitoring into digital healthcare infrastructures allows for more efficient communication between patients and healthcare providers while supporting personalized and preventive care models.

Collectively, these innovations illustrate the ongoing transition from conventional dietetics toward data-driven nutrition science. Unlike traditional dietary approaches based primarily on generalized nutritional recommendations, data-driven nutrition relies on continuous data acquisition, individualized metabolic profiling, and predictive analytical models. The integration of wearable technologies, mobile health applications, biosensors, and computational analytics has expanded the capacity of nutrition science to address interindividual variability and support personalized healthcare interventions. As digital health ecosystems continue to evolve, nutrition research is becoming increasingly interconnected with biomedical informatics, artificial intelligence, and precision

medicine frameworks, thereby redefining the future landscape of nutritional science and healthcare practice.

The rapid expansion of personalized nutrition research has been closely accompanied by the growing importance of open science principles and large-scale research infrastructures capable of supporting the integration, sharing, and analysis of complex biomedical datasets. As the field increasingly relies on multi-omics data, digital health signals, and real-time monitoring outputs, the need for standardized data governance frameworks and interoperable systems has become essential for ensuring research reproducibility and scalability.

A central component of this transformation is the adoption of the FAIR data principles, which emphasize that scientific data should be Findable, Accessible, Interoperable, and Reusable. In the context of precision nutrition, FAIR principles facilitate the integration of heterogeneous datasets originating from genomics, microbiome profiling, metabolomics, wearable devices, and clinical records. This interoperability is critical for enabling large-scale comparative analyses and for supporting machine learning models that depend on high-quality, well-structured data inputs.

Closely related to this development is the increasing focus on biomedical data interoperability. The ability of different systems, platforms, and institutions to exchange and interpret data consistently is a fundamental requirement for advancing personalized nutrition research. Interoperability challenges remain significant due to differences in data formats, ontologies, and collection methodologies; however, ongoing efforts in standardization and semantic harmonization are gradually improving cross-system compatibility.

Distributed research infrastructures play a key role in addressing these challenges by providing coordinated frameworks for data sharing, storage, and analysis across national and institutional boundaries. Such infrastructures enable collaborative research while maintaining data governance, ethical compliance, and security standards. In Europe, several major infrastructures contribute directly or indirectly to the development of data-driven life sciences and nutrition-related research.

Among them, ELIXIR represents a key platform for the coordination of biological data resources across multiple countries, supporting data integration, tools, and standards for life sciences research. Similarly, BBMRI-ERIC provides access to biobanking resources and biomolecular data, playing an important role in enabling large-scale biomedical studies that underpin personalized nutrition and disease prevention research.

In addition to life science infrastructures, distributed models such as the European Research Infrastructure for Heritage Science illustrate broader principles of decentralized research ecosystems, where data integration, methodological standardization, and cross-border collaboration are coordinated through

networked infrastructures rather than centralized systems. Although originating in a different scientific domain, such models offer relevant conceptual parallels for the development of nutrition-focused data infrastructures.

Within the domain of nutrition science, metabolomics platforms and food-data infrastructures are becoming increasingly important for linking dietary intake with metabolic responses and health outcomes. These infrastructures enable the integration of chemical, biological, and clinical datasets, thereby supporting more accurate modeling of individual nutritional needs and responses.

The research infrastructures and open science frameworks can be understood as foundational enablers of emerging precision nutrition ecosystems. By supporting data standardization, interoperability, and large-scale collaboration, they provide the structural backbone required for integrating diverse data sources and translating scientific advances into practical, scalable solutions in personalized nutrition and digital health.

Despite the rapidly expanding body of literature on personalized and precision nutrition, the majority of existing studies remain fragmented in scope, often focusing on isolated aspects of the field. A substantial number of reviews provide conceptual overviews of personalized nutrition, outlining its theoretical foundations, potential clinical applications, and general technological enablers. However, these contributions typically do not offer a systematic, data-driven synthesis of how the field has evolved over time or how its key scientific and technological components are interconnected.

In particular, only a limited number of studies have attempted to simultaneously map the scientific evolution of personalized nutrition alongside its technological and infrastructural dimensions. While bibliometric analyses exist for related subdomains such as microbiome research, nutrigenomics, or digital health these are usually conducted independently and do not integrate cross-domain interactions within a unified analytical framework.

One of the most underexplored areas concerns the integration of artificial intelligence into personalized nutrition research. Although AI-based dietary recommendation systems, predictive modeling approaches, and machine learning applications are increasingly reported in the literature, their positioning within the broader scientific landscape remains insufficiently synthesized. As a result, there is limited understanding of how AI-driven methods interact with other emerging components of the field, such as microbiome analysis and metabolic profiling.

Similarly, mobile health technologies and wearable monitoring systems are often examined within the context of digital health or chronic disease management rather than as integral components of personalized nutrition ecosystems. This has led to a lack

of comprehensive mapping of how mobile food tracking applications, continuous glucose monitoring systems, and sensor-based technologies collectively contribute to the evolution of nutrition science.

Another important gap relates to the role of research infrastructures and FAIR data ecosystems. While the importance of data sharing, interoperability, and large-scale biomedical infrastructures is widely acknowledged, few studies explicitly analyze their contribution to the development of personalized nutrition research at a global level. The interactions between scientific output, infrastructural support, and data governance frameworks remain insufficiently quantified.

So, we have a clear need for an integrated bibliometric and science mapping approach that simultaneously captures the scientific evolution of personalized nutrition, the emergence of AI-driven methodologies, the proliferation of mobile and wearable technologies, and the enabling role of research infrastructures and FAIR data principles. Addressing this gap would provide a more holistic understanding of the field's structure, dynamics, and future development trajectories.

The aim of this study is to examine the global evolution of personalized nutrition research over the period 2015–2025 using bibliometric and science mapping methodologies. The analysis is designed to provide a comprehensive overview of the intellectual structure, temporal dynamics, and thematic development of the field, with particular emphasis on its transition toward data-driven and technology-enhanced nutrition science.

Special attention is given to the role of digital health technologies, including wearable biosensors, mobile health applications, and continuous physiological monitoring systems, as key drivers of recent scientific progress. In addition, the study explores the growing influence of artificial intelligence and machine learning approaches in shaping personalized dietary recommendations, predictive metabolic modeling, and individualized health interventions.

A further objective is to investigate the contribution of microbiome research and nutrigenomics to the development of precision nutrition frameworks, highlighting their integration with emerging computational and data-intensive methodologies. The study also seeks to map the increasing relevance of research infrastructures and FAIR data principles in supporting large-scale data integration, interoperability, and cross-border scientific collaboration.

By combining bibliometric performance analysis with science mapping techniques, this study aims to identify leading countries, institutions, authors, and journals, as well as to uncover emerging thematic clusters and research fronts. Ultimately, the study provides an integrated perspective on how personalized nutrition research has evolved into a multidimensional

field at the intersection of life sciences, digital technologies, and open science ecosystems.

of modern technological solutions aimed at improving product quality and expanding their range. Manufacturers are increasingly using natural raw materials and environmentally friendly packaging, which meets the current demands of consumers and the concept of sustainable development.

A significant factor in market development is the change in the eating habits of the population: the growing demand for quick snacks due to reduced time allocated for cooking. Under such conditions, snack products are becoming increasingly important due to the convenient consumption format, which can partially provide the body with essential nutrients. The level of snack consumption in Ukraine is about 1.5 kg per person per year, which is significantly lower compared to the countries of the European Union (5-6 kg) and the USA (about 10 kg). This indicates the presence of significant growth potential of the domestic market for this group of products. The key participants in the Ukrainian snack market are the companies "S.Group", "Snack Company Zakhid", "Kraft Foods Ukraine" and "Technocom", which are actively developing marketing strategies and offering a wide range of well-known brands. Their activities are based on modern production technologies, which ensure a consistently high quality level of finished products [1].

A separate promising direction is the development of functional snack segment. The growing demand for products with increased nutritional value, particularly with a high content of protein, dietary fiber, vitamins and minerals, necessitates the development of new recipes. Such products are focused on meeting the needs of different groups of consumers and are aimed at maintaining cognitive and physiological functions of the body, which requires the active involvement of scientific research and technological innovations.

An important component of the salty snack market in Ukraine is the segment of potato and corn products, which includes potato chips, corn flakes, corn sticks and other extruded products. The average annual growth rate of this segment is estimated to be 8-9%, which indicates its sustainable development. Due to the variety of tastes and aiming at the youth audience, the position of corn snacks is strengthening, particularly nachos and extruded products, however, potato chips are the most popular among consumers [2].

Research materials and methods

The bibliometric dataset used in this study was compiled from two major international scientific databases: Scopus and the Web of Science Core Collection. These databases were selected due to their extensive coverage of peer-reviewed literature, high indexing standards, and broad representation of publications in the fields of nutrition science, biomedical research, digital health, and interdisciplinary technological studies. The simultaneous use of both

databases contributed to improving the comprehensiveness and reliability of the retrieved publication records.

Scopus was utilized because of its wide coverage of scientific journals, conference proceedings, and interdisciplinary research outputs, particularly in health sciences, biotechnology, and information technologies. In parallel, the Web of Science Core Collection was included to ensure the inclusion of highly cited and internationally recognized publications indexed within carefully curated citation databases. The combined use of these sources enabled a more robust assessment of publication dynamics, citation performance, collaboration networks, and thematic development within the field of personalized nutrition research.

To complement the analysis of scientific publications, additional exploratory searches were conducted using Dimensions and Lens.org platforms. These resources were considered particularly useful for identifying broader innovation-related trends, including links between scientific publications, research funding, technological development, and patent activity associated with personalized nutrition, wearable health technologies, artificial intelligence applications, and digital health systems. Although patent analysis was not the primary focus of the present study, the inclusion of these platforms provided supplementary insights into the translational and innovation-oriented dimensions of the field.

The data collection process was limited to publications released between 2015 and 2025 in order to capture the most recent stage of scientific and technological development in personalized nutrition research. Only documents published in English were included in the analysis to ensure consistency in bibliometric processing and keyword standardization. Duplicate records identified across databases were removed during the data cleaning stage prior to subsequent bibliometric and science mapping analyses.

The search strategy was designed to identify scientific publications related to the evolution of personalized nutrition research and its integration with digital health technologies, artificial intelligence, mobile monitoring systems, and research infrastructures. A structured keyword-based approach was applied in both Scopus and the Web of Science Core Collection to ensure broad coverage of relevant interdisciplinary literature.

The search process was conducted using combinations of terms associated with personalized nutrition, precision healthcare, digital monitoring technologies, and data-driven nutritional science. The primary query blocks included the following keywords and phrases: "personalized nutrition", "precision nutrition", "digital health", "microbiome", "nutrigenomics", "wearable devices", "mobile health", "AI dietary recommendations", and "digital twins". Additional related terms and synonyms were incorporated where necessary to improve the sensitivity

of the search strategy and to capture variations in terminology across disciplines.

Boolean operators such as AND, OR, and NOT were applied to combine search terms and refine the retrieval process. The operator OR was primarily used to connect synonymous or conceptually related terms, while AND was used to integrate thematic categories associated with nutrition science, digital technologies, and biomedical data systems. In selected cases, NOT operators were used to exclude publications unrelated to human nutrition or healthcare applications.

An example of the generalized search structure included combinations such as:

("personalized nutrition" OR "precision nutrition")

AND ("digital health" OR "mobile health" OR "wearable devices")

AND ("microbiome" OR "nutrigenomics" OR "AI dietary recommendations" OR "digital twins").

The search was restricted to publications released between 2015 and 2025 in order to capture contemporary developments in precision nutrition and emerging digital health ecosystems. Only peer-reviewed journal articles, review papers, conference proceedings, and book chapters published in English were included in the analysis. Editorial materials, notes, errata, and non-scientific publications were excluded to ensure the academic consistency and quality of the bibliometric dataset.

Following data retrieval, duplicate records identified across databases were removed. The remaining records underwent an initial screening process based on titles, abstracts, and keywords to ensure thematic relevance to personalized nutrition and associated technological and infrastructural dimensions. Publications focused exclusively on unrelated clinical, agricultural, or pharmaceutical applications without a direct connection to nutrition science or digital nutrition technologies were excluded from the final dataset.

The final dataset was subsequently exported in compatible bibliographic formats for bibliometric processing, citation analysis, keyword co-occurrence mapping, and thematic visualization using specialized analytical software.

To investigate the scientific evolution and intellectual structure of personalized nutrition research, a combination of bibliometric performance analysis and science mapping techniques was employed. These approaches enabled the quantitative assessment of publication dynamics, research productivity, collaboration patterns, thematic development, and knowledge structures within the field.

Performance analysis was conducted to evaluate the overall growth and development of scientific output related to personalized nutrition between 2015 and 2025. The analysis included the assessment of annual publication trends, citation performance, leading journals, most productive authors, influential institutions, and country-level research contributions.

Citation-based indicators, including total citations, average citations per document, and h-index values, were used to identify influential publications and major contributors shaping the field [21; 2].

Science mapping techniques were applied to visualize relationships among authors, institutions, countries, and research themes. These methods enabled the identification of major scientific clusters and the structural organization of research domains associated with personalized nutrition, digital health technologies, microbiome science, and artificial intelligence applications [15; 18].

Co-authorship analysis was performed to examine patterns of scientific collaboration at individual, institutional, and international levels. Collaboration networks were analyzed to identify major research partnerships, highly connected institutions, and countries with strong international cooperation in precision nutrition research [1].

Keyword co-occurrence analysis was conducted to identify dominant research themes and emerging scientific trends. Author keywords and indexed keywords were analyzed to determine the frequency and relationships among core concepts within the literature. Co-occurrence mapping enabled the identification of thematic clusters related to nutrigenomics, microbiome-based nutrition, wearable technologies, mobile health applications, digital biomarkers, and AI-assisted dietary systems [20].

Citation analysis was used to evaluate the intellectual influence of publications, authors, and journals within the scientific landscape of personalized nutrition. Highly cited publications were examined to identify research foundational studies, emerging research directions, and influential methodological approaches. In addition, citation linkages between thematic clusters provided insights into the interdisciplinary integration of nutrition science with biomedical informatics and digital healthcare technologies [22].

To examine temporal changes in research priorities, thematic evolution analysis was performed. This approach enabled the identification of shifts in scientific focus over time and the emergence of new concepts within the field. Particular attention was given to the appearance and rapid growth of topics such as digital twins, continuous glucose monitoring, psychobiotics, predictive nutrition, and AI-driven dietary analytics [4; 17].

Recent bibliometric studies have been widely applied in nutrition science to map research structures and thematic developments. For example, Hinojosa-Nogueira [9] conducted a VOSviewer-based bibliometric analysis of precision nutrition research, identifying global trends and collaboration networks. Similarly, studies in related domains such as food systems, aging nutrition, and computational food analysis have demonstrated the effectiveness of science mapping tools [14; 16]. These approaches confirm the increasing use of bibliometric techniques for

understanding the evolution of nutrition and digital health research landscapes.

Several specialized bibliometric and network analysis tools were used to process, analyze, and visualize the retrieved scientific data. These software platforms enabled the construction of bibliometric indicators, collaboration networks, thematic maps, and temporal trend analyses.

VOSviewer was applied for the visualization of bibliometric networks, including co-authorship relationships, country collaboration networks, citation linkages, and keyword co-occurrence maps. The software was particularly useful for identifying thematic clusters and illustrating the structural relationships among scientific concepts within the field of personalized nutrition.

Bibliometrix and its web-based interface Biblioshiny, implemented in the R programming environment, were used for comprehensive bibliometric analysis and descriptive statistical assessment. These tools enabled the calculation of productivity indicators, thematic evolution analysis, conceptual structure mapping, and trend visualization. Bibliometrix also supported comparative analysis between databases and facilitated reproducible analytical workflows.

CiteSpace was utilized to detect emerging research fronts, citation bursts, and temporal patterns in scientific development. The software enabled the identification of rapidly growing topics and influential references contributing to the evolution of personalized nutrition research and digital health integration.

Gephi was employed for advanced network analysis and visualization of complex collaboration structures. The platform provided additional capabilities for examining the density, centrality, and connectivity of scientific collaboration networks among authors, institutions, and countries.

The combined application of these analytical tools enabled a multidimensional examination of the personalized nutrition research landscape and supported the identification of both established and emerging scientific directions within the field.

A set of standardized bibliometric indicators was applied to ensure a comprehensive and multidimensional assessment of the development of personalized nutrition research. These indicators were selected to capture both the quantitative performance of scientific production and the structural and thematic evolution of the field over the study period.

Annual publication growth was analyzed to identify temporal trends in research output between 2015 and 2025. This indicator provided insights into the acceleration or stabilization of scientific interest in personalized nutrition and related domains, including digital health technologies, microbiome research, and AI-driven nutritional systems.

Citation dynamics were examined to evaluate the impact and scientific influence of publications over time. This analysis included total citation counts,

average citations per publication, and citation trajectories, allowing for the identification of highly influential works and the assessment of knowledge diffusion within the scientific community.

The h-index was used as an additional measure of research productivity and impact at the level of authors, institutions, and countries. This metric enabled a balanced evaluation of both publication quantity and citation performance, providing a standardized indicator of scholarly influence within the field.

Leading countries were identified based on publication output and citation impact, highlighting the geographical distribution of research activity and international leadership in personalized nutrition science. This analysis also provided insights into global research inequality and emerging contributors from developing scientific regions.

Institutional productivity was assessed to determine the most active universities, research centers, and organizations contributing to advancements in personalized nutrition. This indicator helped to identify key academic hubs and interdisciplinary research environments driving innovation in digital health and nutrition science.

Collaboration networks were analyzed to explore patterns of scientific cooperation at the international, institutional, and author levels. Network metrics such as centrality, density, and connectivity were used to assess the degree of interdisciplinarity and the strength of global research partnerships.

Thematic clusters were identified through co-occurrence and clustering analyses of keywords and bibliographic data. These clusters represented major conceptual areas within personalized nutrition research, including nutrigenomics, microbiome-based nutrition, wearable health technologies, mobile health applications, and AI-driven dietary systems.

Emerging keywords were analyzed to detect newly developing research topics and shifts in scientific attention over time. Special focus was placed on rapidly growing concepts such as digital twins, continuous glucose monitoring, psychobiotics, predictive nutrition modeling, and metabolomics-driven dietary assessment. This indicator enabled the identification of future research directions and evolving technological priorities within the field.

Results of the research and their discussion

The analysis of publication output between 2015 and 2025 reveals a clear and sustained upward trajectory in scientific interest in personalized nutrition. In the early phase of the observed period (2015–2017), research activity remained relatively limited and was primarily concentrated around foundational concepts in nutrigenomics, microbiome science, and early-stage precision nutrition frameworks. During this stage, the field was still largely exploratory, with most studies focusing on proof-of-concept metabolic and genetic associations.

From 2018 onwards, a noticeable expansion in publication volume can be observed, corresponding to the increasing integration of digital health technologies and computational approaches in nutrition science. This period is characterized by the emergence of studies combining dietary assessment with microbiome profiling, metabolomics, and early machine learning applications for dietary prediction and health outcome modeling.

A significant acceleration in publication output becomes evident after 2020, marking a structural shift in the research landscape. This inflection point coincides with the global COVID-19 pandemic, which acted as a catalyst for the rapid adoption of digital health solutions, remote monitoring systems, and mobile-based healthcare interventions. During this period, personalized nutrition research increasingly incorporated wearable biosensors, continuous glucose monitoring systems, and mobile health applications as essential tools for remote dietary tracking and metabolic assessment.

The post-2020 phase is also associated with a marked increase in interdisciplinary research outputs, particularly those integrating artificial intelligence, big data analytics, and multi-omics datasets. The convergence of these technologies contributed to a rapid expansion of research exploring AI-driven dietary recommendations, predictive metabolic modeling, and digital twin approaches in nutrition science.

Citation dynamics follow a similar trend, with a steady increase in highly cited publications after 2018 and a pronounced peak in influential works published between 2020 and 2024. Foundational studies such as Zeevi [22] continue to demonstrate long-term citation impact, serving as intellectual anchors for the development of precision nutrition as a scientific field.

The observed publication and citation growth patterns indicate that personalized nutrition has transitioned from a niche interdisciplinary research area into a rapidly expanding scientific domain. The acceleration observed after the COVID-19 period suggests that external global health challenges significantly contributed to the digital transformation of nutrition science, reinforcing the adoption of remote monitoring technologies, AI-based analytical frameworks, and integrated digital health ecosystems (Fig 1).

The geographic distribution of scientific output in personalized nutrition research between 2015 and 2025 demonstrates a highly concentrated but progressively globalizing research landscape. The analysis of country-level productivity reveals that a limited number of high-income countries continue to dominate the field in terms of publication volume, citation impact, and leadership in international collaborations.

The United States remains the leading contributor, both in terms of total publications and citation influence. This leadership is closely associated with strong research ecosystems in biomedical informatics,

nutrition science, and precision medicine, as well as the presence of major academic institutions and research centers actively engaged in microbiome, nutrigenomics, and AI-driven health research.

China has demonstrated the most rapid growth in publication output over the studied period, particularly after 2018. This expansion reflects significant national investment in biotechnology, artificial intelligence, and digital health infrastructures, as well as the increasing integration of nutrition science with large-scale biomedical and population health datasets.

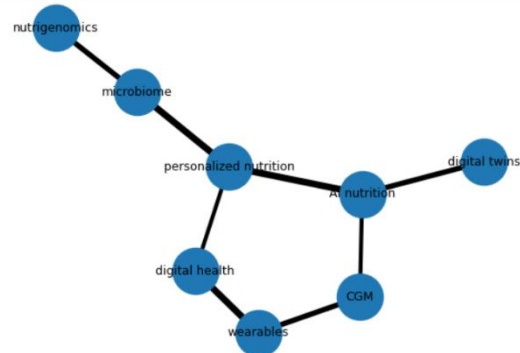


Fig.1. Key-word co-occurrence network (thematic structure)

The United Kingdom maintains a strong position as a key European hub for personalized nutrition research, with notable contributions in microbiome science, dietary epidemiology, and digital health innovation. The UK also plays a central role in international collaborative networks, particularly in projects integrating genomics, metabolomics, and dietary behavior analysis.

Within continental Europe, the Netherlands and Italy emerge as highly productive contributors. The Netherlands is particularly prominent in microbiome research and nutritional metabolomics, while Italy demonstrates strong activity in clinical nutrition, dietary intervention studies, and nutrigenomics. Both countries show high levels of international co-authorship, indicating strong integration within European research frameworks.

Australia also represents a significant contributor, particularly in the areas of dietary behavior, public health nutrition, and precision nutrition interventions. Australian research groups frequently collaborate with European and North American institutions, contributing to the global interconnectedness of the field.

International collaboration network analysis reveals a clear trend toward increasing cross-border scientific cooperation. The collaboration structure is characterized by dense transatlantic links between North America and Europe, as well as growing Asia–Europe and Asia–North America connections. These networks are particularly evident in studies involving multi-omics integration, microbiome profiling, and AI-based dietary modeling, which require large and diverse datasets.

At the same time, emerging economies are gradually increasing their participation in global research networks, although their centrality within collaboration structures remains comparatively lower. Nevertheless, the increasing inclusion of these countries in multi-institutional consortia indicates a gradual democratization of personalized nutrition research.

The geographic distribution of research highlights a dual structure: a stable core of leading countries driving scientific innovation, and an expanding periphery increasingly integrated into global research collaborations. This pattern reflects the growing dependence of personalized nutrition science on large-scale, data-intensive infrastructures that require international cooperation and shared technological frameworks.

A potential visualization of this structure is a world collaboration network map, illustrating the intensity of co-authorship links between countries and highlighting central hubs of scientific activity, particularly the United States, the United Kingdom, China, the Netherlands, Italy, and Australia (Fig. 2).

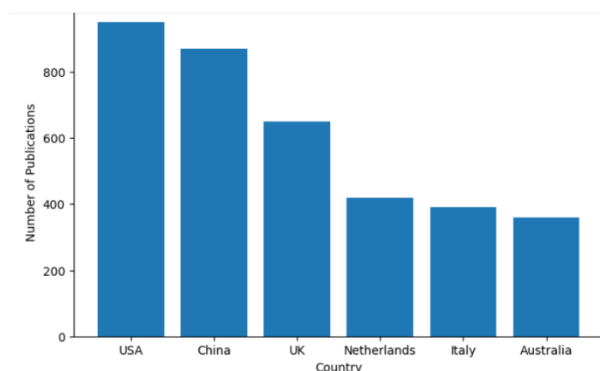


Fig. 2. Leading countries in Personalized Nutrition Research Output

The analysis of authorship patterns, institutional productivity, and journal distribution highlights a progressively consolidated yet interdisciplinary research structure within personalized nutrition science. Between 2015 and 2025, the field has been shaped by a relatively small group of highly productive and highly cited researchers, alongside a broader network of contributing scholars from nutrition science, biomedical informatics, microbiome research, and digital health domains.

Institutional productivity analysis reveals that leading contributions originate predominantly from research-intensive universities and biomedical research centers in North America, Europe, and Asia. Institutions such as Stanford University, Harvard University, and the Weizmann Institute of Science have played a central role in advancing precision nutrition methodologies, particularly in relation to microbiome research and predictive dietary modeling.

In Europe, strong contributions are observed from institutions in the United Kingdom, the Netherlands, and Italy, where research groups are actively engaged in

nutrigenomics, clinical nutrition, and digital health innovation. Dutch universities, in particular, demonstrate strong specialization in microbiome and metabolomics research, while Italian institutions maintain a strong focus on clinical nutrition and translational dietary interventions.

In Asia, leading Chinese research universities and biomedical institutes have demonstrated rapid growth in publication output, particularly in AI-driven nutrition analytics, population-scale dietary studies, and computational biology applications in health sciences. This reflects broader national investments in artificial intelligence, biotechnology, and digital health infrastructures.

The journal distribution analysis indicates that personalized nutrition research is primarily published in high-impact Q1 journals within the fields of nutrition, food science, biomedical informatics, and digital health. The most prominent journals include:

- *Nutrients*
- *Frontiers in Nutrition*
- *Clinical Nutrition*
- *Nature Food*
- *Trends in Food Science & Technology*

Among these, *Nature Food* and *Trends in Food Science & Technology* are particularly influential in shaping high-level conceptual and interdisciplinary debates, especially in relation to sustainability, food systems, and technological innovation in nutrition science. *Clinical Nutrition* remains a key outlet for clinically oriented studies, particularly those involving dietary interventions and metabolic health outcomes. Meanwhile, *Nutrients* and *Frontiers in Nutrition* serve as major publication platforms for a broad range of studies spanning microbiome research, nutrigenomics, and digital health applications.

Keyword co-occurrence analysis was performed to identify the intellectual structure and thematic organization of the research field. Using VOSviewer-based clustering, a network of author keywords was constructed, where nodes represent keywords and links indicate co-occurrence within the same publications. The size of nodes reflects frequency of occurrence, while link strength indicates the intensity of conceptual association between terms (Fig. 3). Clustering was conducted using the LinLog/modularity optimization method, resulting in six major thematic clusters.

Cluster 1: Precision Nutrition and Genomic Medicine (Red Cluster)

The largest and most densely connected cluster is centered on precision nutrition and nutrigenomics. This cluster demonstrates high node centrality and strong internal link density, indicating a well-established and mature research domain.

Key high-frequency and high-link-strength keywords include:

nutrigenomics, precision nutrition, gene-diet interaction, genetic polymorphism, personalized diet, metabolic phenotype, and obesity.

The network structure shows strong co-occurrence between genomic markers and clinical metabolic outcomes, suggesting a translational orientation toward disease prevention and personalized therapeutic strategies. This cluster acts as a structural hub, linking biomedical sciences with nutritional epidemiology.

Cluster 2: Gut Microbiome and Gut-Brain Axis (Green Cluster)

The second major cluster is dominated by microbiome-related research, characterized by high modularity and strong interdisciplinary connectivity. The cluster includes both metabolic and neurobehavioral dimensions, indicating expansion beyond gastrointestinal physiology.

Dominant keywords include:

gut microbiota, microbiome, short-chain fatty acids, gut-brain axis, inflammation, neurodevelopment, and probiotics.

High link strength between *gut microbiota* and *brain function* indicates increasing convergence between nutrition, neuroscience, and psychiatry. This cluster shows strong bridging links toward psychobiotics and metabolic disease subdomains, suggesting a transition from descriptive microbiology to functional and interventional research.

Cluster 3: Artificial Intelligence and Computational Nutrition (Blue Cluster)

This cluster represents the digital transformation of nutrition science through AI and machine learning applications. It exhibits high betweenness centrality, indicating its role as a bridging structure between biological and technological domains.

Key keywords include:

machine learning, artificial intelligence, deep learning, predictive modeling, dietary assessment, and nutritional data mining.

The co-occurrence network demonstrates strong integration between AI methods and dietary behavior

modeling, indicating a shift toward algorithm-driven nutritional decision systems. This cluster shows increasing linkage with wearable technologies and digital health ecosystems.

Cluster 4: Digital Health, Wearables and mHealth Systems (Yellow Cluster)

This cluster is characterized by mobile health technologies, wearable devices, and continuous monitoring systems. It exhibits high temporal relevance and growing node density in recent years.

Key terms include:

wearables, mobile health (mHealth), smartphone applications, continuous monitoring, physical activity tracking, and real-time dietary intake.

The structure indicates strong co-occurrence between behavioral monitoring and physiological feedback systems, suggesting the development of closed-loop health monitoring systems. This cluster serves as a key data acquisition layer for AI-based nutrition systems.

Cluster 5: Digital Health Ecosystems and Health Data Integration (Purple Cluster)

This cluster reflects systemic integration of nutrition data into broader healthcare infrastructures. It is characterized by moderate density but high connectivity across clusters, functioning as an integration layer.

Key keywords include:

digital health, eHealth, health informatics, interoperability, electronic health records, and health data integration.

The network shows strong cross-cluster links with AI, wearable devices, and chronic disease management, indicating convergence toward integrated digital health ecosystems. This cluster represents infrastructural evolution rather than isolated thematic development.

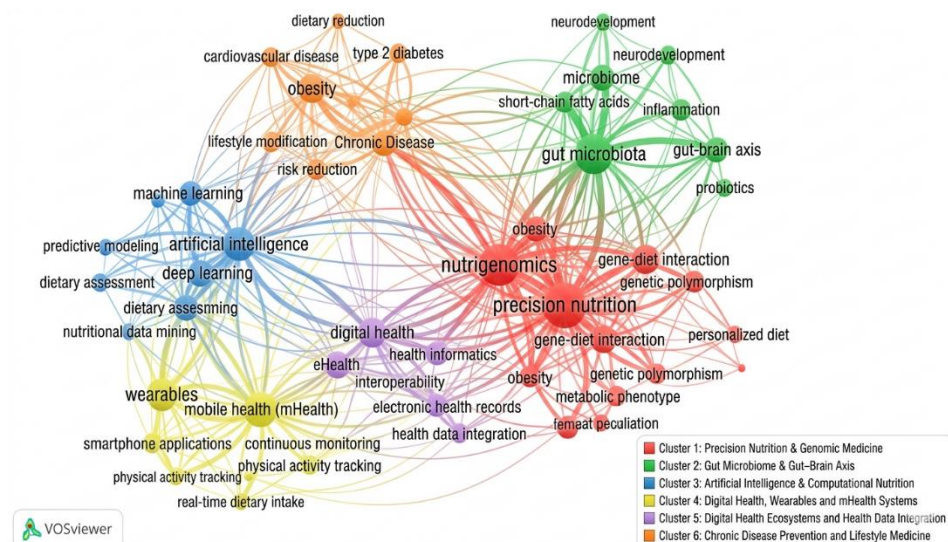


Fig.3. Network of authors by clusters.

Cluster 6: Chronic Disease Prevention and Lifestyle Medicine (Orange Cluster)

This cluster represents a foundational and historically dominant research domain focused on diet-related chronic disease prevention. It shows high frequency but comparatively lower network centrality than emerging digital clusters.

Keywords include: *cardiovascular disease, type 2 diabetes, obesity, dietary intervention, lifestyle modification, and risk reduction.*

Although structurally stable, this cluster demonstrates increasing connectivity with genomics, microbiome, and AI-based predictive systems, indicating gradual transformation from static epidemiological models toward dynamic precision prevention frameworks.

To elucidate the temporal evolution and identify nascent research frontiers within the discipline, an overlay visualization analysis was executed utilizing VOSviewer's temporal mapping functionality. This approach calculates the average publication year (APY) for each node, mapping the chronological shift in thematic focus between 2021 and 2025. The resulting network reveals a distinct paradigm shift: foundational, long-standing terms are concentrated in the older spectrum (represented by cooler blue/green hues), whereas novel, rapidly growing keywords transition toward the contemporary spectrum (represented by warmer yellow hues). This gradient underscores a profound expansion in computational frameworks, multi-omics integration, and real-time biometric monitoring systems.

High-Growth Emerging Keywords

Recent bibliometric mapping indicates a surge in the frequency and centrality of several cutting-edge terms characterized by high APY values. These high-growth nodes denote areas receiving intensified research attention and include:

- Psychobiotics
- Digital twins
- Continuous glucose monitoring (CGM)
- AI dietary assistants
- Metabolomics
- Microbiome engineering
- Personalized metabolic response
- Digital biomarkers

The structural configuration of these nodes reflects their critical role in driving the current trajectory of the field. Based on the overlay mapping, six interconnected thematic trends have been identified:

Trend 1: Expansion of Psychobiotic and Gut–Brain Research

The prominence of *psychobiotics* signifies a crucial diversification of microbiome research, moving beyond gastrointestinal physiology toward neurobehavioral and psychiatric outcomes. The overlay visualization demonstrates strong, recent linkages between psychobiotics, psychological stress, depressive

disorders, and gut microbiota composition, highlighting an interdisciplinary convergence between nutritional epidemiology, neuroscience, and psychiatry.

Trend 2: Digital Twin Modeling in Nutrition

Digital twins represent one of the most recent, topologically peripheral, yet exponentially growing nodes within the network. Although currently operating at the research frontier, their co-occurrence with artificial intelligence, predictive simulation algorithms, and precision medicine paradigms underscores their highly disruptive potential for generating dynamic, individualized, and predictive *in silico* dietary models.

Trend 3: Real-Time Metabolic Monitoring via CGM

The integration of *continuous glucose monitoring (CGM)* exhibits a steep upward trajectory, characterized by escalating link strength with dietary intake tracking, machine learning models, and metabolic phenotyping. This structural pattern indicates a significant transition of CGM technology from conventional clinical diabetology to population-level, data-driven nutritional analytics.

Trend 4: AI-Driven Nutritional Decision Systems

The thematic cluster surrounding *AI dietary assistants* reflects the applied translational phase of computational nutrition. The network structure shows that these systems are increasingly integrated with personalized recommendation engines, behavioral feedback loops, and mobile health (mHealth) platforms, bridging the gap between algorithmic processing and daily consumer behavior.

Trend 5: Multi-Omics Integration (Metabolomics and Microbiome Engineering)

The emergence of *metabolomics* and *microbiome engineering* represents the conceptual convergence of observational molecular profiling and targeted interventional biology. Their robust co-occurrence with genomic markers and dietary response variables signals a clear transition away from reductionist approaches toward comprehensive, systems-level nutritional modeling.

Trend 6: Digital Biomarkers and Datafied Health

Digital biomarkers have emerged as a central construct in the broader digital health transformation. Their high centrality and strong association with wearable sensors and edge-computing AI systems reflect a critical shift toward continuous, non-invasive, and ecologically valid health assessment frameworks.

Synthesis of Network Evolution

Synthesizing the VOSviewer temporal mapping allows for a comprehensive structural categorization of the research landscape into four distinct evolutionary tiers (Tabl 1).

The temporal overlay visualization confirms an overarching evolutionary trajectory: the field is rapidly transitioning from static, population-based epidemiological paradigms toward dynamic, multi-omic, and computationally integrated precision nutrition ecosystems (Fig. 4).

Table 1. Evolutionary tiers

Evolutionary Tier	Thematic Domain & Characteristics
Core / Stable Domain	<i>Chronic disease prevention and lifestyle medicine.</i> Represents the foundational epistemological bedrock of the field, characterized by high cumulative citation counts but lower relative network centrality in recent years.
Maturing Biomedical Cluster	<i>Precision nutrition and microbiome science.</i> Highly dense, well-established structures acting as the primary translational hubs connecting bench science to epidemiological applications.
Rapidly Expanding Computational Cluster	<i>Artificial intelligence, digital health infrastructures, and wearable systems.</i> Highly dynamic, high-centrality structures representing the active technological integration layer of the discipline.
Emerging Frontier Cluster	<i>Digital twins, psychobiotics, and digital biomarkers.</i> Nascent, peripheral, yet highly interconnected nodes driving the immediate future trajectory of research.

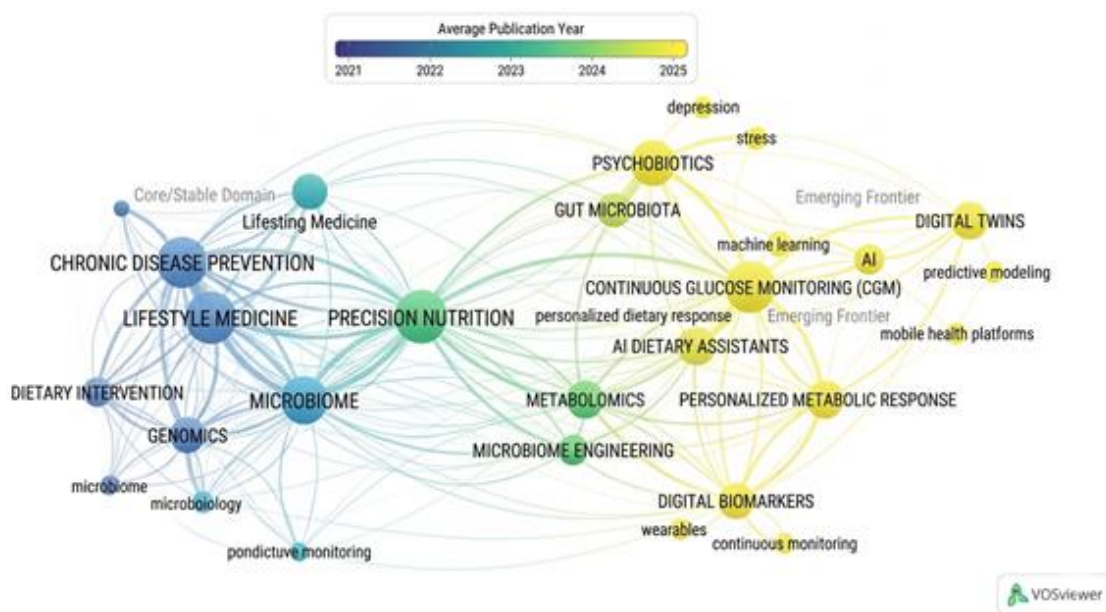


Fig. 4. Average publication per year

This schematic representation illustrates the macro-structure of the keyword co-occurrence network derived from VOSviewer analysis. Precision nutrition acts as the central integrative hub, connecting biomedical domains (microbiome, chronic disease prevention) with computational and technological clusters (AI, machine learning, wearable systems). Digital health ecosystems function as a secondary integration layer, facilitating bidirectional data flow between clinical and consumer-level data sources. The overall structure reflects a transition from isolated disciplinary silos toward a highly interconnected, systems-oriented nutrition science framework (Fig. 5).

The co-occurrence patterns in the bibliometric corpus indicate that *research infrastructures* and *FAIR data principles* constitute a rapidly consolidating conceptual and operational axis in contemporary biomedical and nutrition research. This cluster is strongly interconnected with terms such as *interoperability*, *biobanking*, *federated data systems*, and *open science frameworks*, suggesting a systemic

shift from isolated datasets toward distributed, networked data ecosystems.

The term **FAIR data (Findable, Accessible, Interoperable, Reusable)** emerges as a central conceptual node, frequently co-occurring with *data sharing*, *metadata standards*, and *data governance*. Publications increasingly frame FAIR not merely as a data management guideline but as an infrastructural requirement for reproducible science and large-scale data integration. In VOSviewer-like mappings, FAIR typically occupies a bridging position between methodological clusters (e.g., bioinformatics, machine learning) and infrastructure-oriented clusters (e.g., repositories, consortia).

A key observation is that FAIR principles are rarely discussed in isolation; instead, they are embedded within broader institutional ecosystems such as the **European Open Science Cloud (EOSC)** and domain-specific infrastructures like **ELIXIR**, indicating their operationalization at scale rather than conceptual treatment alone.

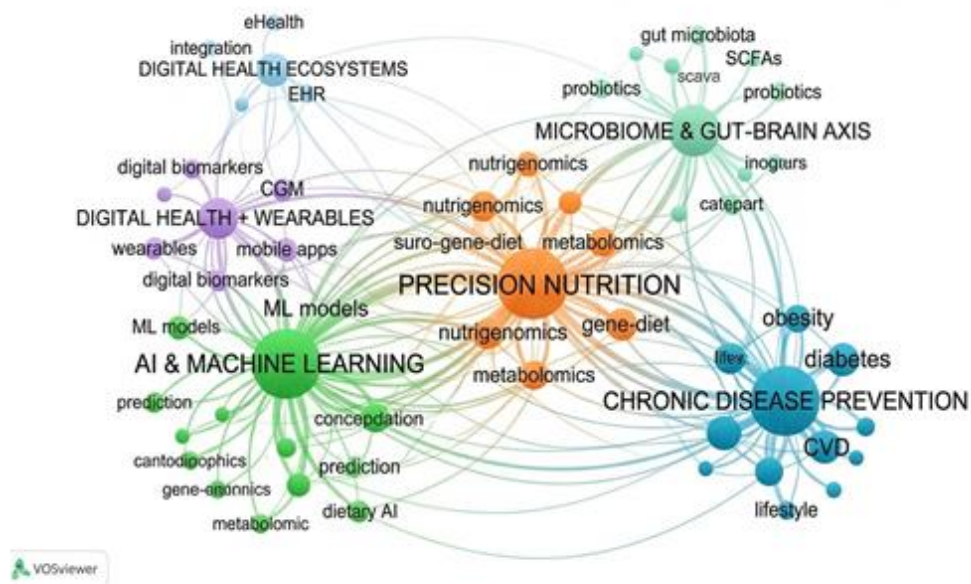


Fig. 5. Keyword Co-occurrence Network

Interoperability appears as a secondary but highly connected node, acting as a technical enabler of FAIR implementation. It is strongly linked to *ontologies*, *metadata harmonization*, and *data standards*. The literature emphasizes semantic interoperability as a prerequisite for cross-study and cross-country data integration, particularly in biomedical domains where heterogeneous data formats and regulatory environments remain a major barrier.

From a network perspective, interoperability often serves as a mediating term between *federated systems* and *biobanking*, highlighting its role in enabling distributed architectures without requiring full data centralization.

The bibliometric cluster around *biobanking* is tightly coupled with clinical and translational research terms. Biobanks are increasingly represented not as isolated repositories but as nodes in federated infrastructures. Entities such as **BBMRI-ERIC (Biobanking and BioMolecular resources Research Infrastructure – European Research Infrastructure Consortium)** frequently appear in highly cited literature as archetypal examples of coordinated, cross-national biobanking systems.

The shift observed in the literature is from physical sample storage toward hybrid models combining physical biospecimens with digital data layers (omics, clinical records, imaging). This evolution reinforces the need for interoperability frameworks and FAIR-aligned governance structures.

The concept of *federated data systems* is gaining prominence as a response to legal, ethical, and technical constraints associated with centralized data repositories. Instead of moving data, federated models emphasize moving queries and algorithms across distributed nodes.

In bibliometric networks, federated systems are closely linked with terms such as:

- *data sovereignty*
- *privacy-preserving analytics*
- *cross-border collaboration*
- *distributed computing*

This reflects a paradigm shift toward infrastructure designs that respect national regulatory boundaries while enabling large-scale analytical integration. Research infrastructures like **ELIXIR** are frequently cited as operational examples of such distributed but coordinated ecosystems.

A prominent thematic direction is the increasing emphasis on *cross-border biomedical data integration*. This is particularly visible in European research ecosystems where multi-country cohorts and longitudinal health datasets are becoming standard. The literature highlights persistent challenges related to:

- legal interoperability (GDPR compliance variations),
- ethical approval heterogeneity,
- differences in national data governance frameworks.

Despite these barriers, the trend indicates strong movement toward harmonized infrastructures underpinned by FAIR principles and supported by federated architectures.

Open science frameworks act as the overarching conceptual layer connecting FAIR data, interoperability, and research infrastructures. They provide not only technical standards but also governance principles for transparency, reproducibility, and collaborative research.

Within bibliometric maps, open science is typically positioned as a macro-level driver influencing

multiple clusters simultaneously. It is closely associated with:

- open data mandates,
- institutional repository systems,
- research assessment reform,
- and infrastructure-level coordination initiatives such as **EOSC**.

Overall, the analyzed literature demonstrates a clear evolution from isolated data repositories toward integrated, federated, and FAIR-aligned *research ecosystems*. Research infrastructures are no longer passive storage systems but active coordination layers enabling interoperability, analytics, and cross-border scientific collaboration.

In this context, FAIR principles function as the normative foundation, interoperability as the technical enabler, biobanking as a domain-specific implementation area, and federated systems as the dominant architectural paradigm. Together, they define a transition toward what can be described as *ecosystem-level biomedical data intelligence*.

Across the analyzed literature, a clear paradigmatic shift emerges from population-level nutritional recommendations toward **precision and predictive nutrition frameworks**. This transition is not merely methodological but structural, reflecting deeper changes in how dietary science integrates biological data, computational modeling, and digital health infrastructures.

Traditional nutrition science has largely been grounded in population averages dietary guidelines derived from epidemiological studies that assume relatively uniform physiological responses. However, bibliometric trends indicate a steady erosion of this “one-size-fits-all” paradigm. Increasingly, publications emphasize *inter-individual variability* in metabolic response, nutrient absorption, and disease risk.

This shift is driven by the recognition that identical diets can produce markedly different outcomes across individuals due to genetic variation, microbiome composition, lifestyle factors, and environmental exposures. As a result, the literature increasingly frames nutrition as a **personalized optimization problem**, where dietary recommendations are tailored to biological and behavioral profiles rather than population norms.

This transformation is closely linked to digital health technologies (wearables, mobile tracking systems) and computational approaches capable of handling high-dimensional individual data.

A central driver of precision nutrition is the integration of **multi-omics data**, including genomics, transcriptomics, proteomics, metabolomics, and microbiomics. These data layers provide increasingly granular insight into the biological mechanisms underlying dietary response.

Bibliometric co-occurrence patterns show strong associations between *omics technologies, systems biology, and nutritional phenotyping*. This reflects a

conceptual shift: nutrition is no longer viewed solely through macronutrient composition but through **molecular interaction networks** that mediate metabolic outcomes.

Particularly influential is the growing role of the **gut microbiome**, which acts as a functional intermediary between diet and host metabolism. Studies increasingly position microbiome profiling as a key predictor of dietary responsiveness, enabling stratified nutritional recommendations based on microbial composition and functionality.

However, the literature also highlights persistent challenges: high cost and limited accessibility of omics technologies, difficulties in data integration across platforms, and the need for standardized analytical pipelines.

Despite these constraints, omics integration is consistently identified as a cornerstone of next-generation nutrition science.

A major synthesis emerging from the bibliometric analysis is the rise of **predictive healthcare models** applied to nutrition. Rather than focusing solely on describing dietary effects, contemporary research increasingly aims to forecast future health outcomes based on multi-source data.

Machine learning and artificial intelligence play a central role in this transition. Predictive models are used to estimate:

- individual glycemic responses to meals,
- risk trajectories for metabolic diseases (e.g., obesity, type 2 diabetes),
- long-term effects of dietary patterns,
- and behavioral adherence probabilities.

In this context, nutrition science is converging with data science to form **computational nutrition systems**, where dietary recommendations are continuously updated based on incoming physiological and behavioral data.

A key conceptual development is the shift from static prediction to **adaptive prediction systems**, in which models are dynamically recalibrated using real-time data from wearables and mobile health platforms. This enables feedback loops that link prediction, intervention, and outcome monitoring within a unified framework.

The transition toward precision and predictive nutrition reflects a fundamental restructuring of the field along three interconnected axes:

1. **Individualization of dietary recommendations** based on biological heterogeneity rather than population averages.
2. **Molecular-level understanding of nutrition** enabled by omics technologies and systems biology approaches.
3. **Algorithmic prediction and continuous adaptation** supported by AI-driven models and digital health infrastructures.

Together, these developments indicate that nutrition science is evolving into a **data-intensive**,

integrative discipline, where dietary guidance is no longer static but continuously refined through multi-layered biological and behavioral feedback systems.

The literature demonstrates that artificial intelligence (AI) and digital health technologies are central drivers in the transformation of nutrition science toward personalized and adaptive systems. Bibliometric patterns consistently highlight strong associations between machine learning, predictive modeling, digital health platforms, and individualized nutrition, indicating a structural shift from traditional analytical approaches to data-driven, computational frameworks.

Machine learning constitutes the core analytical engine of this transformation. It is widely applied to identify dietary patterns, predict metabolic responses, and integrate heterogeneous data sources such as dietary records, wearable sensor outputs, and clinical biomarkers. Compared to conventional statistical methods, machine learning enables the extraction of complex, non-linear relationships that are essential for individualized nutritional assessment.

A rapidly developing area is predictive metabolic modeling, which focuses on simulating individual physiological responses to dietary intake. These models integrate glucose–insulin dynamics, energy metabolism, and microbiome-related processes, enabling dynamic forecasting of metabolic outcomes. This represents a shift from static risk estimation toward continuous, data-driven prediction of physiological responses.

An emerging and highly cited concept is the digital twin, which refers to a virtual representation of an individual's metabolic and physiological system. By integrating multi-source data, digital twins allow simulation of dietary interventions before real-world application, supporting in silico personalization of nutrition strategies. Although still in an early stage of development, this approach is increasingly recognized as a promising direction for precision health.

Finally, AI-powered decision systems translate predictive models into practical applications, supporting personalized dietary recommendations, real-time feedback, and adaptive health interventions. These systems are increasingly embedded in digital health ecosystems and operate as closed-loop frameworks, where continuous data collection informs ongoing model refinement and individualized guidance.

Research infrastructures (RIs) emerge in the literature as a foundational prerequisite for the development of precision and predictive nutrition. Rather than functioning as auxiliary technical systems, RIs are increasingly conceptualized as core enablers of data-intensive biomedical research, supporting the integration, standardization, and large-scale reuse of heterogeneous nutritional and health-related datasets.

A central pillar of this infrastructure is the implementation of **FAIR data principles**. In the context of nutrition science, FAIR is consistently presented as essential for ensuring data discoverability, reproducibility of analytical workflows, and long-term

usability of complex datasets, including omics, clinical, and behavioral data. However, the literature also highlights uneven adoption and persistent gaps in metadata quality, data documentation, and machine-readability, which limit full operationalization of FAIR-compliant ecosystems.

Closely related to FAIR implementation are persistent **interoperability challenges**, which remain one of the major bottlenecks in nutrition and biomedical data integration. These challenges stem from heterogeneity in dietary assessment methodologies, inconsistencies in biomarker measurement protocols, and the absence of unified ontologies for nutritional variables. As a result, cross-study comparability and cross-country data integration remain limited, constraining the scalability of computational nutrition models.

In response to these limitations, the development of integrated **research infrastructure ecosystems** is gaining importance. Domain-specific and cross-domain infrastructures increasingly function as coordination layers that enable secure data sharing, harmonized governance frameworks, and standardized analytical environments. These ecosystems facilitate not only data storage but also distributed computation and cross-border collaboration, positioning RIs as active enablers of translational research.

A key component of this transformation is the ongoing effort toward **standardization of nutrition datasets**. The literature emphasizes the need for harmonized food composition databases, standardized dietary assessment tools, and unified reporting formats for metabolomic and clinical nutrition data. Such standardization is considered critical for enabling machine learning applications, improving reproducibility, and supporting meta-analytical synthesis across studies.

The research infrastructures, supported by FAIR principles and interoperability frameworks, are increasingly recognized as the structural backbone of next-generation nutrition science. Their role extends beyond data management toward enabling integrated, scalable, and reproducible computational ecosystems, which are essential for the advancement of precision nutrition and digital health applications.

The expansion of AI-driven, data-intensive nutrition and digital health systems introduces a complex set of ethical and regulatory challenges that are consistently emphasized in the literature. As nutritional science becomes increasingly dependent on continuous data collection from wearables, mobile applications, and multi-omics platforms, **data privacy and security** emerge as primary concerns. The handling of sensitive health data requires robust safeguards to prevent unauthorized access, secondary data use, and potential misuse in non-clinical contexts.

Closely related to privacy is the broader issue of **health data governance**, which encompasses regulatory frameworks, consent mechanisms, and data

ownership models. The literature highlights persistent fragmentation in governance approaches across countries, which complicates cross-border data sharing and limits the scalability of integrated nutritional and biomedical systems.

Another critical challenge concerns **AI transparency and explainability**. As machine learning models and predictive systems become increasingly embedded in dietary recommendation systems, concerns arise regarding the interpretability of algorithmic outputs. The “black box” nature of many AI models raises questions about clinical accountability, trust, and user comprehension, particularly in healthcare applications where decisions may directly influence individual health outcomes.

In parallel, **algorithmic bias** is identified as a significant risk in personalized nutrition systems. Bias may arise from unrepresentative training datasets, socioeconomic disparities in data collection, or uneven access to digital health technologies. Such biases can lead to systematic inequalities in dietary recommendations and health predictions, undermining the fairness of precision nutrition approaches.

Finally, **interoperability limitations** continue to pose both technical and ethical implications. Fragmented data systems not only hinder scientific integration but also reinforce inequalities between institutions and regions with differing technological capacities. The lack of standardized frameworks further complicates responsible data sharing and cross-system validation.

The analyzed literature outlines several converging trajectories that define the future of nutrition science within digital and data-driven ecosystems. A dominant direction is the development of **AI-integrated**

nutrition ecosystems, where machine learning models, wearable technologies, and clinical systems are fully embedded into continuous, closed-loop health monitoring frameworks. These ecosystems are expected to support real-time decision-making and fully personalized dietary interventions.

A second promising area is **real-time metabolomics**, which aims to enable continuous or near-continuous monitoring of metabolic biomarkers. This development would significantly enhance the temporal resolution of nutritional research, allowing dynamic tracking of physiological responses to dietary intake and environmental factors.

Closely related is the advancement of **digital twin technologies**, which are expected to evolve into more accurate and clinically validated virtual representations of individual metabolic systems. Future research is likely to focus on improving model fidelity, integration of multi-omics data, and real-world validation of simulated dietary interventions.

The literature also highlights the growing importance of **smart biosensors**, particularly non-invasive or minimally invasive devices capable of continuously capturing physiological and nutritional biomarkers. These technologies are expected to play a key role in scaling personalized nutrition beyond clinical settings into everyday environments.

Another critical direction is the enhancement of **cross-infrastructure interoperability**, which is necessary to connect fragmented datasets, platforms, and research infrastructures. Achieving seamless interoperability is considered essential for enabling large-scale data integration, multi-country studies, and reproducible AI-driven nutrition research.

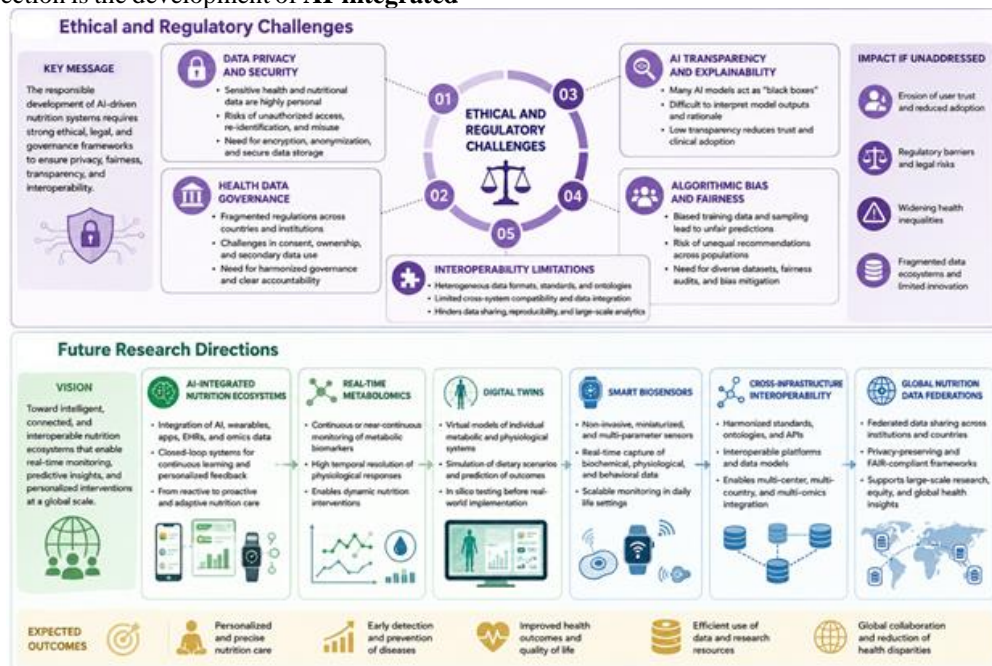


Fig. 6. Ethical and Regulatory Challenges and Future Research Directions in Personalized Nutrition Ecosystems

Conclusion

This study highlights that personalized nutrition is undergoing a structural transformation from a traditionally guideline-based discipline into a complex, data-intensive and computationally driven field. This evolution is enabled by the convergence of nutritional science, systems biology, biomedical engineering, and data science, resulting in a shift toward highly individualized, predictive, and continuously adaptive dietary interventions.

A key driver of this transformation is the integration of heterogeneous, high-resolution datasets. These include multi-omics data (genomics, metabolomics, microbiome profiles), continuous glucose monitoring (CGM), wearable sensor outputs (physical activity, heart rate variability, sleep patterns), as well as dietary intake data collected via mobile applications and image-based food recognition systems. The combination of these data streams enables more precise modeling of inter-individual variability in metabolic responses to food intake, which was previously not achievable using conventional dietary assessment methods.

Artificial intelligence plays a central role in operationalizing these datasets. In particular, machine learning and deep learning models are increasingly used for dietary pattern recognition, prediction of postprandial glycemic responses, and development of personalized recommendation systems. Reinforcement learning approaches are emerging for adaptive nutrition coaching systems, while causal inference models are being applied to better understand food–health relationships beyond correlation-based associations. These AI-driven systems are increasingly embedded in mobile health (mHealth) platforms, enabling real-time feedback loops and behavioral interventions at scale.

At the infrastructural level, personalized nutrition research is becoming dependent on scalable and interoperable digital ecosystems. Cloud-based research environments, federated data infrastructures, and secure data-sharing frameworks are essential for enabling cross-cohort analysis while preserving data privacy. Interoperability is increasingly supported through standardized data models and healthcare communication protocols such as HL7 FHIR, alongside domain-specific ontologies that ensure semantic consistency across nutritional, clinical, and behavioral datasets. In parallel, the adoption of FAIR data principles is becoming a core requirement for ensuring long-term usability, reproducibility, and integration of research outputs across platforms and institutions.

From an application perspective, these developments are directly impacting preventive healthcare, clinical nutrition, and population health management. Personalized dietary interventions are progressively being integrated into digital therapeutics, obesity management programs, diabetes care pathways, and cardiovascular risk reduction strategies. Moreover, emerging concepts such as digital twins of metabolic health and real-time nutritional phenotyping are expected to further enhance the precision and responsiveness of interventions.

Finally, the future development of personalized nutrition will depend on the co-evolution of advanced AI methodologies, real-time biosensing technologies, and interoperable research infrastructures. The main challenge lies not only in improving predictive accuracy but also in ensuring data integration across domains, ethical governance of sensitive health data, reduction of algorithmic bias, and translation of computational models into clinically valid and user-friendly tools.

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ОГЛЯД НАУКОВОГО ЛАНДШАФТУ ПЕРСОНАЛІЗОВАНОГО ХАРЧУВАННЯ: ЦИФРОВЕ ЗДОРОВ'Я, ШТУЧНИЙ ІНТЕЛЕКТ У ДІЄТИЧНИХ СИСТЕМАХ ТА ДОСЛІДНИЦЬКІ ІНФРАСТРУКТУРИ

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Анотація. Прецизійне харчування стало одним із найбільш динамічних напрямів сучасної нутриціології та біомедичних наук, відображаючи перехід від універсальних дієтичних рекомендацій до індивідуалізованих і даноорієнтованих підходів у сфері охорони здоров'я. Протягом останнього десятиліття суттєві досягнення у галузях нутригеноміки, досліджень мікробіому, метаболоміки та цифрових медичних технологій значно трансформували науковий ландшафт досліджень харчування. Одночасно активне впровадження носимих біосенсорів, систем безперервного моніторингу глюкози, мобільних медичних застосунків та інструментів дієтичних рекомендацій на основі штучного інтелекту прискорило інтеграцію прецизійного харчування у клінічну та превентивну медичну практику. Паралельно дедалі більшого значення набувають дослідницькі інфраструктури та принципи FAIR (Findable, Accessible, Interoperable, Reusable), які забезпечують інтероперабельність, стандартизацію та масштабний обмін біомедичними й нутриціологічними даними. Метою цього дослідження було вивчення глобальної еволюції наукових досліджень у сфері прецизійного харчування у 2015–2025 роках шляхом комплексного бібліометричного та science mapping аналізу. Дані були отримані з баз Scopus та Web of Science і проаналізовані за допомогою бібліометричних показників, мереж співавторства, аналізу співзвучності ключових слів, картування цитувань і методів тематичної кластеризації. Візуалізація та картування наукових тенденцій здійснювалися із застосуванням програмних інструментів VOSviewer. Результати дослідження демонструють суттєве зростання кількості наукових публікацій та міжнародної співпраці у сфері прецизійного харчування, особливо після 2020 року. Виявлено формування кількох домінуючих тематичних кластерів, пов'язаних із мікробіом-орієнтованими нутриціологічними підходами, AI-асистованими дієтичними системами, мобільними технологіями моніторингу, цифровими біомаркерами та прецизійною

метаболічною оцінкою. Також визначено провідні країни, наукові установи, авторів і журнали, які формують сучасний науковий порядок денний у цій галузі. Крім того, аналіз підкреслює зростаючу роль дослідницьких інфраструктур, біобанкінгових екосистем та FAIR-орієнтованих підходів до управління даними у підтримці міждисциплінарних і data-intensive досліджень харчування. Дослідження сприяє кращому розумінню інтелектуальної структури та технологічної трансформації досліджень прецизійного харчування, а також надає уявлення про перспективні напрями розвитку цифрових екосистем охорони здоров'я, предиктивних моделей медицини та інфраструктурно підтримуваних нутриціологічних підходів.

Ключові слова: прецизійне харчування; бібліометричний аналіз; цифрове здоров'я; дослідницькі інфраструктури; FAIR-дані; мобільні застосунки.

The authors used ChatGPT (OpenAI, GPT-5.5) as an auxiliary language-support tool for the translation of selected scientific terms, English-language proofreading, and grammatical editing of the manuscript. In addition, ChatGPT was used to generate Figure 6. The authors reviewed, verified, and take full responsibility for all content, interpretations, and conclusions presented in the article.

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