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Multi-Omics and Artificial Intelligence in Functional Food Innovation: Current Progress and Future Perspectives

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ABSTRACT: The importance of the development of functional food with bioactive compounds with scientifically proven physiological effects is significant as a good strategy to provide health and prevent chronic diseases. The development of multi-omics technologies such as genomics, transcriptomics, proteomics, metabolomics, microbiomics, and foodomics has greatly improved the understanding of the nutrient–host interactions and the molecular mechanisms involved in the functional efficacy of food. At the same time, AI has revolutionized the functional food research field by allowing for the efficient integration of multi-omics data from large cohorts, predictive modeling, the discovery of biomarkers, and the development of personalized nutrition. The review highlights the latest developments in the integration of multi-omics and AI tools in functional food innovation and their applications in bioactive compound identification, food quality and safety testing, precision nutrition, and prevention of diseases. The review also addresses nutrigenomics, nutrition of the gut microbiome, and digital health technologies of personalized functional foods using AI. Furthermore, key data integration, data standardization, explainable AI, and ethical and regulatory issues are discussed thoroughly. The prospects focus on the integration of multi-omics, wearable technology, and precision nutrition with AI to enable the rapid development of next-generation functional foods. Finally, the combination of multi-omics and AI provides a holistic systems biology view, allowing for evidence-based functional food innovation, individual nutrition for optimal health, and sustainable nutrition strategies for the benefit of the planet.

1. INTRODUCTION

According to the University of Maryland Medical Centre, functional food is a food that works in a way different from its nutritional value to promote health and prevent diseases through bioactive compounds like polyphenols, antioxidants, flavonoids, dietary fibre, probiotics, prebiotics, bioactive peptides, and omega-3 fatty acids. Chronic non-communicable diseases (NCDs), like obesity, diabetes, cardiovascular diseases (CVDs), cancer, and neurodegenerative diseases, have become more common worldwide and have gained more interest as a potential tool in preventive medicine and health promotion (1). Concurrently, the idea of personalized nutrition has expanded, suggesting that people's responses to nutritional components are likely to be highly dependent on their genetic background, metabolic traits, gut microbiota composition, environmental factors, and lifestyle, and that consequently, food interventions will be more personalized than current, generic nutrition guidance (2). The advancement of multi-omics technologies has greatly facilitated the study of functional foods and their molecular mechanisms, such as genomics, transcriptomics, proteomics, metabolomics, and microbiomics, and has enabled the comprehensive understanding of the molecular mechanisms of the health effects of functional foods (3). When taken together, these complementary omics datasets can be used to discover biomarkers, understand nutrient–gene interactions, characterize metabolic pathways, and discover novel bioactive compounds with more therapeutic potential (4). However, the complexity, dimensionality, and heterogeneity of multi-omics data is massive and require sophisticated computational methods that can capture valuable biological information. Artificial intelligence (AI), in particular machine learning and deep learning algorithms, has proven to be a game-changing technology for combining multiple omics data sets, uncovering unknown biological relationships and trends, predicting the functional properties of food-derived bioactive compounds, discovering biomarkers associated with diseases, and precision nutrition strategies with higher precision and efficiency (5). As a result, the integration of multi-omics technologies and AI has created a strong basis for the future of intelligent, preventative and personalized nutrition by powering nutrition-driven precision healthcare, evidence-based product development, improved nutrition plans and enhanced personalized nutrition.

2. MULTI-OMICS TECHNOLOGIES IN FUNCTIONAL FOOD RESEARCH

The development of multi-omics technologies has become crucial tools used for the advancement of the functional food research and provide a holistic view on the molecular mechanism by which food bioactive compounds affect human health. Genomics studies genetic variations like single nucleotide polymorphisms (SNPs) that affect the way nutrients are metabolized, and the risk for disease, response to functional foods, and aims to develop precision nutrition strategies (7). The other major approach to genomics is complemented by transcriptomics, which studies changes in gene expression that occur in response to dietary interventions, aiding in identification of signaling pathways and molecular responses linked to the health promoting activities of functional food ingredients such as polyphenols, flavonoids, probiotics and dietary fiber (8). Proteomics also adds to this knowledge by examining the expression of proteins, post-translational modifications, enzyme activities and cellular signaling networks that control physiological effects caused by bioactive food components and compounds to understand how they prevent disease or how they are used in therapeutic approaches. (9) Metabolomics is a novel technique for global analysis of endogenous and exogenous metabolites in biological samples which would aid in the identification of a reliable biomarker for nutritional status, metabolic health and disease progression and would be able to provide a wide-range elucidation of the metabolic effects of functional food consumption.Concurrently, the study of the gut microbiome is emerging as a critical science for understanding the composition and functional activity of the gut microbiota and their interactions with dietary components to regulate immune response, energy metabolism, inflammation and production of beneficial microbial metabolites (e.g., short-chain fatty acids) towards personalized nutrition intervention (11). The term "Foodomics" is the new emerging term that describes the application of genomics, transcriptomics, proteomics, metabolomics, microbiomics and advanced bioinformatics in a new comprehensive systems biology approach to the study of the food composition, quality, safety, authenticity, bioactivity and health effects at the molecular level. The all-encompassing strategy enables new functional ingredients to be identified, nutritional and health claims to be validated and food processing methods optimized, as well as providing the opportunity to develop new functional food formulations tailored to each organism. Combined, these complementary multi-omics approaches provide an unprecedented systems level view that enriches the discovery of biomarkers, understanding of nutrient–host interactions, precision nutrition and rapid evidence based functional food innovation to benefit human health and prevent chronic disease (12).

3. ARTIFICIAL INTELLIGENCE IN FUNCTIONAL FOOD INNOVATION

Artificial intelligence (AI) also has become a game-changing technology in functional food innovation, as it has the ability to analyze and interpret complex multi-omics data obtained from genomics, transcriptomics, proteomics, metabolomics, microbiomics, and foodomics studies. Machine learning (ML) algorithms can detect hidden associations between biological variables, classify functional food ingredients, predict biological activities, and create formulation strategies, while deep learning (DL) models can uncover the complex nonlinear relationships between high-dimensional data to enhance predictions of nutrient–gene interactions, efficacy of bioactive compounds, and responses to individual diets (13). These computational methods greatly speed up the discovery and development of new functional foods and diminish the experimental cost and time. Finally, predictive analytics can use heterogeneous biological and clinical data to predict disease risk, nutritional results, consumer responses, and product performance to support evidence-based decision making and targeted nutrition interventions, which further enhances functional food research (14). Virtual screening of natural bioactive compounds, optimizing food processing conditions, quality assessment, shelf-life prediction, and safety evaluation are other applications of AI-driven predictive models, which enhance the efficiency of research and industrial use. Moreover, the importance of AI-driven discovery of biomarkers can't be overstated for precision nutrition, as it enables the identification of molecular signatures linked to health status, metabolic disorders, gut microbiome composition, and dietary intervention responses. Multiple omics technologies are combined within advanced AI algorithms, thereby helping to identify clinically relevant biomarkers that enable early disease detection, monitoring of therapeutic response, and personalised diet recommendations (16). By combining AI with multi-omics technologies, researchers can build a systems biology framework that transforms vast amounts of biological data into knowledge and can help them design new functional foods that are more effective, safe, and personalized. The integrated workflow (Figure 1) spans from the acquisition of various types of 'omics' data to the use of AI for data processing, identification of biomarkers, predictive modeling, and the development of personalized functional foods, demonstrating the pivotal role of AI in the future development of precision nutrition and functional food innovations.

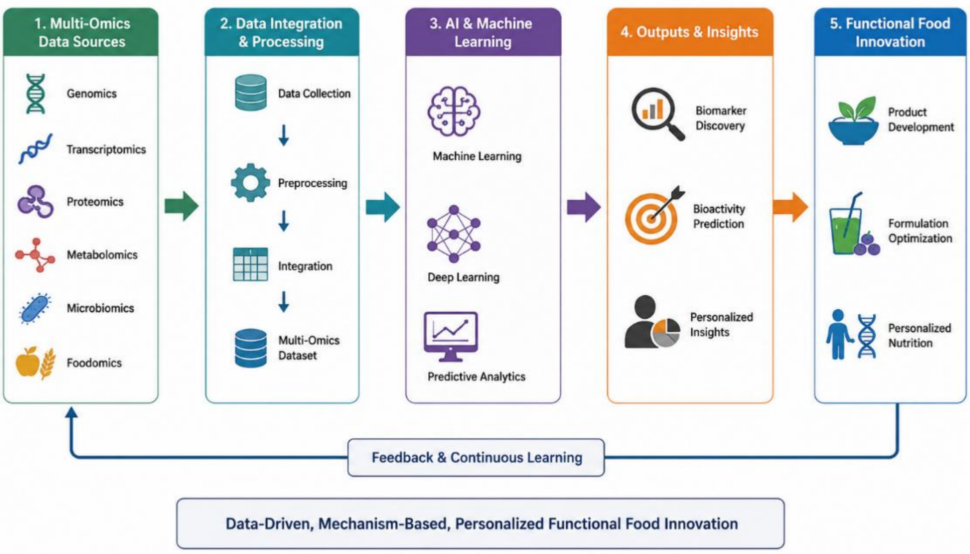

Figure 1. Integrated Data-Driven Framework for Multi-Omics Analysis, Predictive Analytics, and Personalized Nutrition.

4. APPLICATIONS IN FUNCTIONAL FOOD DEVELOPMENT

The integration of multi-omics technologies and artificial intelligence has significantly expanded the applications of functional food development by enabling the design of evidence-based nutritional interventions tailored to individual health needs. Precision nutrition has emerged as one of the most promising applications, utilizing genomic, metabolomic, microbiomic, and phenotypic information to develop personalized dietary recommendations that optimize metabolic health, reduce disease risk, and improve therapeutic outcomes according to an individual's biological profile (17). AI-assisted analysis of multi-omics datasets also accelerates the discovery of novel bioactive compounds from plant, microbial, marine, and food sources by predicting their biological activities, molecular targets, pharmacokinetic properties, and safety profiles, thereby reducing the time and cost associated with conventional experimental screening methods (18). Furthermore, advanced computational approaches improve food quality and safety through rapid assessment of food composition, authentication, contamination detection, shelf-life prediction, and monitoring of nutritional quality, ensuring the production of safe, standardized, and high-quality functional food products (19). Functional foods developed using integrated omics and AI approaches also contribute substantially to disease prevention and health promotion by modulating metabolic pathways, enhancing immune function, regulating gut microbiota, reducing oxidative stress and chronic inflammation, and lowering the risk of major non-communicable diseases such as obesity, diabetes, cardiovascular diseases, cancer, and neurodegenerative disorders (20). Collectively, these technological advances are transforming functional food research from a traditional nutrition-based approach into a data-driven precision healthcare platform capable of delivering personalized, safe, and scientifically validated nutritional solutions for improving human health and long-term disease prevention.

5. AI-DRIVEN PERSONALIZED FUNCTIONAL FOODS

AI has transformed the way personalized functional food development works, by integrating multi-omics data and advanced computational models to create tailored nutrition plans that take into account an individual's unique biological makeup. Given the important role that the composition and metabolic function of intestinal microorganisms play in the regulation of nutrient metabolism, immunity and susceptibility to disease, gut microbiome-based nutrition is a key area of precision nutrition. Personalized functional foods can be designed using AI algorithms built with a combination of microbiome sequencing data and metabolomic and clinical data to enhance gut health and metabolically balance an individual's response to food (21). Nutrigenomics and nutrigenetics extend this personal nutrition concept by considering the ability of the nutrient composition of food to modulate the expression of genes and the effect of genetic variation on the response to a specific nutritional program. Genomic, transcriptomic and metabolomic data, in combination with machine learning, can be used for the identification of gene–nutrient interaction, which enables personalised dietary recommendations to optimize health outcomes and reduce the risk of chronic diseases (22). In addition, digital health technologies and wearables have revolutionized the monitoring of nutrition in real time, collecting information from glucose levels to physical activity, from heart rate to sleep quality, and much more, including dietary habits. These are combined with multi-omics data into AI-driven analytical platforms that generate dynamic dietary recommendations, monitor the effect of dietary interventions, and adapt the ingestion of functional food in accordance with physiological changes (23). With the use of AI, multi-omics technologies and digital health platforms, an intelligent precision nutrition ecosystem is established, which allows the development of personalized functional food and improves disease prevention, optimizes metabolic health, and enables evidence-based nutrition management for different populations (24).

Table 1. Applications of Multi-Omics and Artificial Intelligence in Functional Food Innovation

Technology	Application	Major Outcome
Genomics	Nutrigenomics	Personalized dietary recommendations
Transcriptomics	Gene expression analysis	Mechanism of nutrient action
Proteomics	Protein profiling	Biomarker identification
Metabolomics	Metabolic profiling	Disease risk assessment
Microbiomics	Gut microbiome analysis	Precision microbiome-based nutrition

Foodomics	Food quality evaluation	Functional ingredient discovery
Artificial Intelligence	Multi-omics integration	Predictive analytics and decision support
Machine Learning	Bioactive compound prediction	Accelerated functional food development
Deep Learning	Biomarker discovery	Precision nutrition and disease prevention
Digital Health & Wearables	Real-time monitoring	Personalized nutrition management

6. CHALLENGES AND FUTURE PERSPECTIVES

Although multi-omics technologies and artificial intelligence are making tremendous strides towards multi-omics science, a number of scientific, technical, regulatory and ethical barriers still exist to widespread use in functional food innovation. Integration and standardization of multi-omics data from genomics, transcriptomics, proteomics, metabolomics, microbiomics and foodomics platforms are one of the key challenges. Experimental protocols, data quality, analytical approaches and bioinformatics pipelines can differ between studies, leading to discrepancies in data sets, making it challenging to reproduce the results or to compare between studies (25). For the reliable integration of multiple omics data, the standardization of protocols, interoperability of databases and the creation of strong computational frameworks is therefore crucial. Also, the challenge of complex AI models to be understood is a problem. Although deep learning algorithms are highly predictive, they are not widely used in clinical practice, because they are not biologically interpretable. An Explainable Artificial Intelligence (XAI) approach that can predict the development of expertise in a transparent, interpretable and biologically meaningful manner is essential to inform scientific confidence and evidence-based decision making in precision nutrition (26). Regulatory and ethical issues are also substantial challenges, such as data privacy, cybersecurity, informed consent, algorithmic bias, ownership of biological data and harmonised international guidelines for creating functional foods with the aid of AI and for personal nutrition (27).Future studies ought to focus on how multimodal biological information can be combined with digital health technologies, wearable biosensors, cloud computing, and generative AI for real-time nutrition monitoring, intelligent decision support, and tailored nutrition plans. Ongoing progress in systems biology, federated learning, digital twin and precision nutrition will facilitate the identification of new functional food ingredients, more effective disease prevention approaches and more personalized nutrition solutions by AI, thereby opening the door to a more sustainable healthcare. The future calls for a progressive integration of multi-omics technologies, explainable AI, digital health and precision nutrition, towards next-generation functional food innovation and personalized healthcare, as shown in Figure 2 (28).

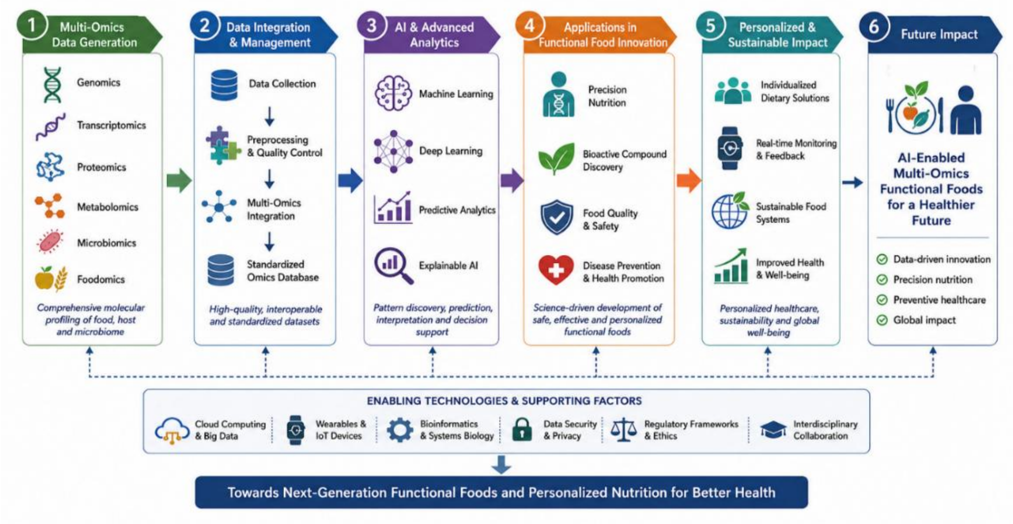

Figure 2. AI-Driven Multi-Omics Pipeline for Functional Food Development and Personalized Healthcare.

7. CONCLUSION

Multi-omics technologies combined with artificial intelligence are changing the way the research of functional foods is conducted to give a comprehensive understanding of the molecular mechanisms of nutrition and health. Thanks to the synergy between genomics, transcriptomics, proteomics, metabolomics, microbiomics, and cutting-edge AI algorithms, it is possible to identify precise biomarkers, develop personalized nutrition strategies, identify bioactive compounds by intelligent methods, and develop functional foods based on scientific evidence. Innovations serve to enhance the quality, safety, and disease prevention of food and help satisfy the needs of precision healthcare via personalized dietary interventions. While data integration, standardization, data interpretability, and regulatory barriers still exist, ongoing progress in explainable AI, digital health, and systems biology is anticipated to overcome these barriers. In summary, AI-driven multi-omics platforms are a game-changer for creating the next generation of functional foods to support global health, sustainable nutrition, and personalized healthcare.

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