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PERSPECTIVE ARTICLE

Personalized and precision medicine as a health-care model of the next step generation through translational applications of individualized nutrition- and food design-driven resources

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Abstract

In the modern era, health is a key element in shaping the trajectory of human civilization. The personalized and precision medicine model is a preventive strategy capable of operating across a wide range of technological applications, from biomarker-driven genomic profiling to determine the characteristics of an individual's genomic landscape, to combinatorial assessments of the individual's interaction with the microenvironment for constructing the individual phenotype. Omics technologies demonstrate their multidisciplinary potential in pre-clinical screening, predictive and prognostic diagnosis, multidimensional monitoring, and targeted therapy, through the prism of preventive and curative rehabilitation strategies concerning a particular individual, as well as the principles and resources of genomic biostatistics and molecular epidemiology at the population and national levels. Therefore, this article aims to highlight the omics approach to nutritional assessment and dietary recommendations from the individual to the population level.

Keywords: Omics technology; Genetics; Proteomic; Metabolomic; Biomarkers; Interactomics

1. Introduction

The progress of health-saving technologies has substantially transformed modern health care, presenting personalized approaches that are both pioneering and effective. Among these, personalized nutrition (PN) and precision foodomics (PF) have emerged as significant fields, taking advantage of the power of omics technologies to provide tailored nutritional advice and interventions. This personalized approach is critical for addressing the unique health needs of individuals, enhancing overall well-being, and preventing nutrition-related diseases. In this context, the main objective of PN and PF is to promote and improve health by utilizing omics, phenotypic, medical, nutritional, and other relevant personal data to provide more precise dietary guidance and customized nutritional products and services. These approaches can be applied to patients, individuals at risk, and healthy individuals, regardless of whether they have a genetic predisposition to specific disorders, including metabolic and nutritional conditions[1-8] (Figures 1 and 2).

Health-saving technologies aim to prevent and delay illnesses, improve well-being, and reduce health-care needs, with nutrition being a key determinant of individual health outcomes. Diets can increase disease risk or promote better health depending on their genetic impact. Nutrigenomics explores the connection between food and genetics and facilitates innovations in health care. Developments in wearable devices and artificial intelligence (AI)-assisted diagnostics empower individuals and enable individualized, patient-centered care. These technologies help improve health-care access and ensure quality medical expertise is available to all. By adopting these innovations, we can transform health care and build a healthier, more resilient world for everyone.

2. Omics technologies: The new generation of health-saving technologies

The development of multiomics technologies, which include transcriptomics, proteomics, epigenomics, metabolomics, and microbiomics, has significantly enhanced our ability to interpret genomic data and improve health outcomes. By integrating these interconnected datasets, integrative multiomics offers a more comprehensive understanding of human health and disease. Health-saving technologies, embedded within the infrastructure of the model of personalized and precision medicine (PPM), represent a unique preventive strategy (Figures 3 and 4).

Multiomics technologies operate with large amounts of data to identify the relationships between biological processes at various levels, the dynamics of borderline states with induction of pathological processes, and the development of optimal protocols for targeted therapy. With the introduction and study of systems omics technologies, the mechanisms of induction, development, and progression of chronic health conditions, including nutritional and hereditary conditions, have moved from hypothetical approaches to diagnosis, treatment, and prevention to integrated strategies[16] (Figures 5 and 6).

Omics technologies, including genomics, proteomics, metabolomics, and microbiomics, are at the forefront of PPM. These technologies offer an in-depth analysis of biological molecules, revealing intricate interactions among genes, proteins, and metabolites. By integrating multiomics data, researchers and health-care providers can enhance their understanding of an individual's overall health condition, facilitating precise and personalized interventions. The omics technologies applied in PN are particularly transformative. Nutrigenomics, a subfield of omics, studies how food affects gene expression and how genetic variations alter the body's response to nutrients. This knowledge allows for the development of dietary proposals tailored to the genetic predispositions of each individual, improving health outcomes and preventing chronic diseases. Several fundamental areas of omics technology and their potential applications are discussed in the following sections.

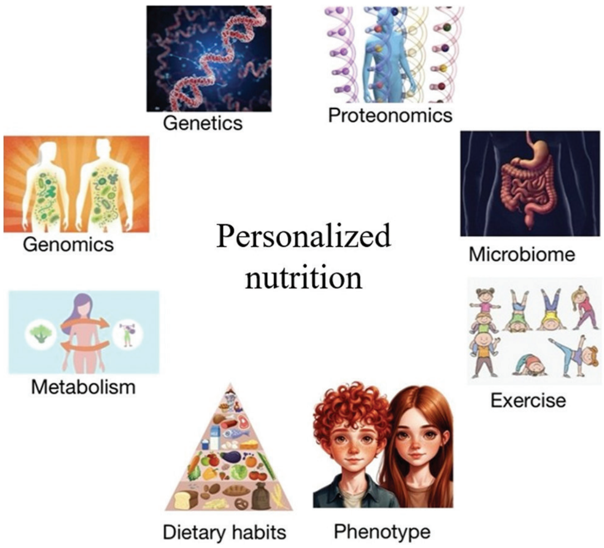

Figure 1. Personalized nutrition includes several factors, such as the genome, metabolome, microbiome, lifestyle, diet, and phenome. Personalized nutrition utilizes advanced analytical technologies to efficiently manage and provide detailed information about individuals' genetics, metabolomes, microbiomes, and phenomes. Within this paradigm, the integration of advanced omics technologies with comprehensive phenotyping has the potential to reveal previously undiscovered hereditary factors and gene–environment interactions.[9,10]

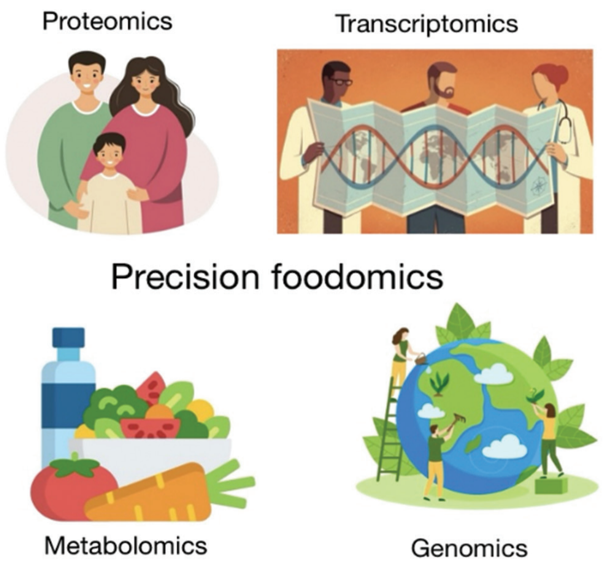

Figure 2. Precision foodomics is a new discipline that was introduced as a global strategy through the application of advanced omics in the food science domain. It examines the food and nutrition domains through the application and integration of advanced omics technologies. Precision foodomics is already a widely used methodology in food science analyses. Both targeted and non-targeted approaches using transcriptomics, proteomics, metabolomics, and genomics are discussed, along with an overview of data integration in multiomics datasets to fully interpret the results from a global precision foodomics perspective.[11,12]

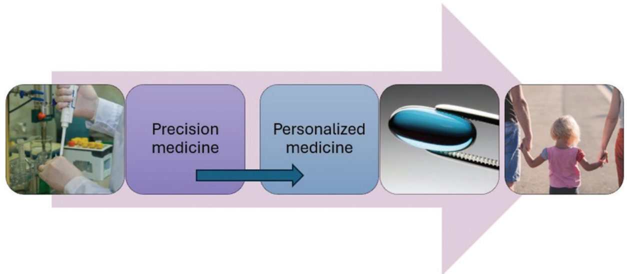

Figure 3. A basic framework of information technology-integrated PPM. Precision medicine identifies differences among individuals, categorizing them based on environmental, biological, and psychosocial factors. Personalized medicine takes these differences and implements prevention and treatment tailored to each individual. Powered by high-throughput omics technologies and computational capabilities, PPM provides multi-scale, in-depth insights into cells, organisms, and populations. By leveraging these conceptual and technological advancements, PPM is built on two core pillars: Data generation and data modeling. High-throughput omics technologies facilitate the acquisition of comprehensive and holistic biological information, while computational advancements enable high-dimensional data modeling, making the analysis both accessible and user-friendly. The current focus on biologic omics in discussions of PPM should not divert attention from traditional approaches to personalized care, including clinical evaluation, the importance of clinician–patient rapport, and addressing social determinants of health and lifestyle behaviors. To achieve further improvements in health care, progress on all of these fronts must continue, not solely in omics-based PPM.[13]
Abbreviation: PPM: Personalized and precision medicine.

2.1. Genomics

PPM adapts therapies, disease prevention, and health maintenance to meet patients' unique needs. Various therapy types—such as proteins, nucleic acids, viruses, cells, genes, and irradiation—can benefit from genomics. This shift expands the importance of pharmacogenomics and nutrigenomics in medicine. PPM seeks to enhance patients' health care by utilizing predictive genomic biomarkers with the aim of improving patient outcomes and minimizing the risk of adverse effects[19,20] (Figure 7).

Metabolic and nutritional disorders are increasingly prevalent worldwide. PPM has the potential to address a wide range of illnesses and equip physicians with the tools to predict the most effective treatment for patients with metabolic disorders or implement preventive measures for individuals at risk. Identifying key diagnostic and predictive biomarkers is essential for developing targeted treatment plans for metabolic and nutritional diseases, using a comprehensive analysis of metabolomic, proteomic, genetic, and clinical data. To achieve this, real-time modeling of clinical data alongside multiple omics datasets is crucial, as it helps uncover underlying biological mechanisms, risk factors, and other valuable information that support early diagnosis and prevention of chronic or complex diseases. Integrating advanced technologies such

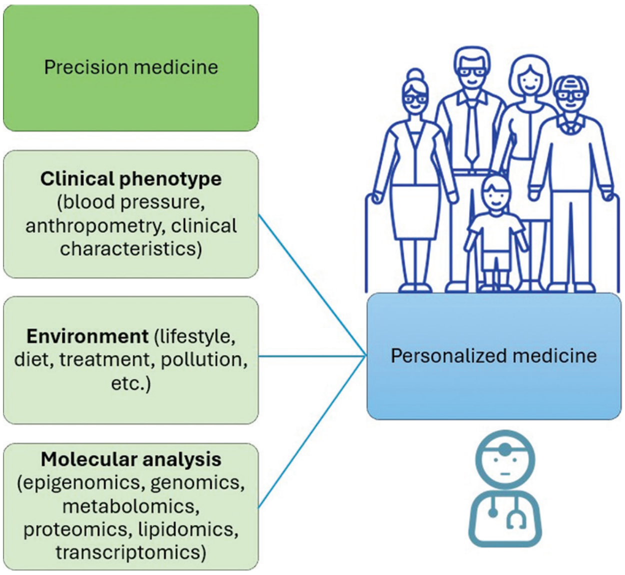

Figure 4. PPM represents an ambitious challenge for medicine and health-care services, aiming to ensure targeted care pathways through more personalized approaches from the outset. PPM has emerged as a prominent topic across various research fields and is likely to play a crucial role in the future. The growing interest in this area can be attributed to the advancements in systems biology and high-throughput technologies. Notably, the expanding knowledge and improved interpretation of genetic data will deepen our understanding of physiological processes in health and disease, paving the way for more precise diagnoses and personalized treatment. This approach can also help reduce the burden of disease by enhancing prevention and treatment strategies through the integration of multiple data sources. Furthermore, PPM seeks to lower health-care costs and minimize adverse events by optimizing the selection of the right therapy at the right time for each patient. Successfully implementing PPM into clinical practice requires a comprehensive, multi-level approach to patient care. At the molecular level, the multiomics approach—including transcriptomics, metabolomics, genomics, proteomics, and epigenomics—offers a deeper understanding of patient conditions, from the underlying causes of diseases to their functional consequences. This information should be integrated with the study of the "exposome," which encompasses the totality of an individual's lifetime exposures and their impact on health. By combining these insights with clinical patient data, physicians can develop personalized therapies tailored to each individual.[14,15]
Abbreviation: PPM: Personalized and precision medicine.

as AI and machine learning (ML) is vital for consolidating diverse data, analyzing multiple variables, building clinical biomarker databases to aid decision-making, and creating ethical protocols to address these challenges.[21,22]

In recent decades, genome-wide association studies (GWAS) have been employed to identify the genetic foundations of chronic diseases, uncovering the impact of various common genetic variants on disease risk. These disorders include—but are not limited to—cardiovascular disease (CVD), cancer, metabolic, neurodegenerative, and neuropsychiatric ailments. Nonetheless, despite the significant hereditary component observed in these chronic illnesses, the genetic variants identified explain only a small portion of disease variability. These genetic variants typically have a small effect, contributing to disease treatment models via polygenic risk scores (PGS), also known as polygenic risk indicators. PGS are quantitative factors that capture the cumulative influence of several common genetic variants on a specific condition or illness. Calculated as the sum of the risk alleles in an individual, PGS are weighted according to the effect sizes of these alleles, as estimated by independent phenotype-training GWAS. Thus, PGS assesses a person's genetic predisposition to a trait or disease, based on their genotype profile and using independent GWAS information as a learning model.[15,23]

There is a strong rationale for integrating PGS with other risk algorithms incorporating environmental components to forecast the risk of chronic diseases in routine clinical practice. For example, CVD has a substantial dataset with the potential for cost-effective application of PGS.[15,23] However, current dietary guidelines for CVD remain a topic of debate. A pooled analysis involving 172,891 participants revealed 9,453 cases of coronary heart disease (CHD) and 8,182 cases of stroke. In addition, an updated meta-analysis drew evidence from 49 previous non-overlapping studies, which showed varying associations for different types of saturated fatty acids (SFAs). Even-chain SFAs were positively associated with CVD risk, whereas odd-chain and longer-chain SFAs had a negative association. Overall, higher total levels of n-3 polyunsaturated fatty acids (PUFAs) were linked to a lower risk of CHD, whereas higher total n-6 PUFAs were associated with a reduced risk of stroke. When examining individual PUFAs, linoleic acid—the predominant n-6 PUFA—along with docosahexaenoic acid and n-3 docosapentaenoic acid, was negatively associated with the risks of CHD and stroke. In contrast, dihomo-γ-linolenic acid was positively associated with both diseases. Interestingly, α-linolenic acid, an n-3 PUFA mainly found in plant sources, did not show a relationship with lower risks of CHD or stroke. Furthermore, arachidonic acid, a key metabolite of linoleic acid, was not linked to an increased risk of either condition.[24]

Although 30–50% of common cancers are attributable to lifestyle and environmental factors, cancer remains a considerable global health burden, with 20 million new cases in 2022. Prevention is the most effective and economical strategy for cancer control, underscoring the need for tools that support public adherence to preventive guidelines. Adherence to the World Cancer Research Fund and the American Institute for Cancer Research's Cancer Prevention Recommendations is associated with

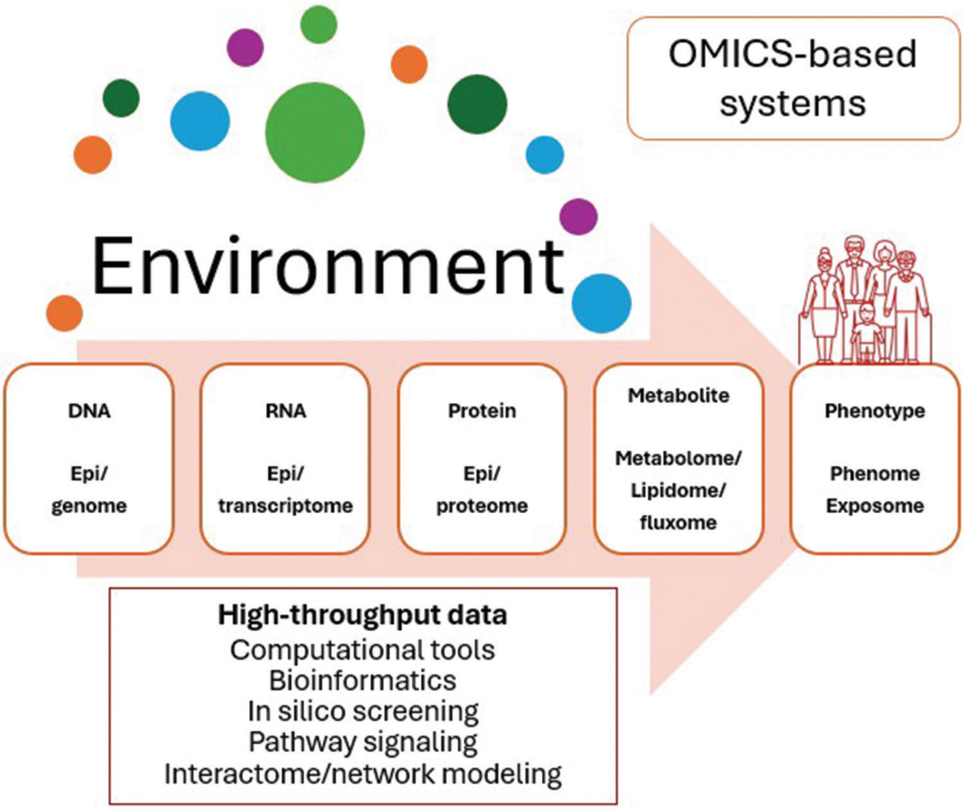

Figure 5. Building blocks of the omics approach in PPM. Omics technologies are the cornerstone of PPM, encompassing high-throughput analyses such as genomics, transcriptomics, proteomics, and metabolomics/lipidomics. These approaches, when integrated with robust systems biology, bioinformatics, and computational tools, enable the comprehensive study of cellular mechanisms, interactions, and functions across tissues, organs, and the entire organism. By operating at the molecular level in a non-targeted and unbiased manner, omics technologies provide a deeper understanding of biological complexity and disease processes.[17]
Abbreviation: PPM: Personalized and precision medicine.

a lower risk of cancer and better survival rates. However, no rapid, validated tools currently exist to assess individual adherence. To address this, Chaplin *et al.*[25] developed and validated a 13-item screening tool that evaluates compliance with seven of the 10 recommendations issued in 2018 by the World Cancer Research Fund and the American Institute for Cancer Research, with the assessment taking <6 min to complete. The tool provides both overall and recommendation-specific scores (met, partially met, and not met), facilitating targeted prevention strategies. This tool supports the implementation of comprehensive lifestyle interventions that lower the risk of cancer and other chronic diseases.

Nevertheless, clinical recommendations for primary prevention do not suggest using genetic information to assess risk. This is because none of the PGS with high predictive power have demonstrated the ability to modify treatment in a cost-effective manner or encourage patients to change their lifestyles.[15,23] Although most relevant and recent studies conducted in developing countries have shown a significant improvement in net risk reclassification, a cost-benefit analysis is required to corroborate its clinical usefulness in risk assessment. Several factors must be considered essential, including the number of participants, the expenses of assessing health indicators, and the management of false positives. Furthermore, significant challenges include the prohibitive cost of laboratory testing and the relatively modest increase in predictive accuracy.

In addition to authorized translational genomics and pharmacogenomics-driven approaches, nutrigenetics and nutrigenomics, along with other omics technologies, are becoming increasingly essential in PN-based care to understand how an individual responds to nutrition-driven therapy. Nutrigenetics and nutrigenomics, along with regular omics tools, serve as instruments to create goals for more accurate nutrition evaluation. They offer valuable insights into molecular mechanisms, as individual nutritional needs can differ greatly. Omics testing reveals modest individual variability and is essential for leveraging this data in PN development. While diet-based therapies

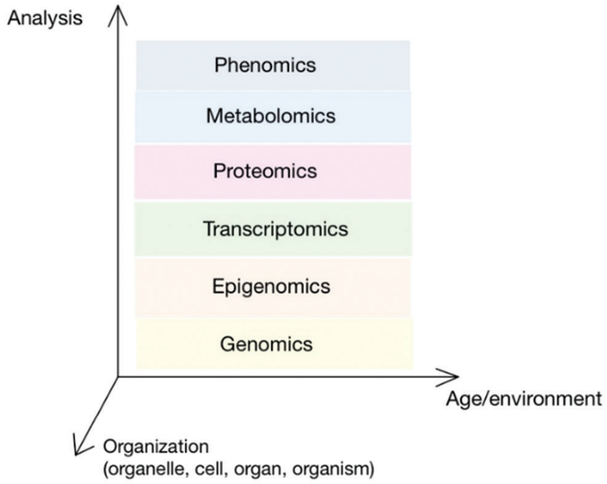

Figure 6. Multiomics data encompass information from various omics disciplines, including genomics, epigenomics, transcriptomics, proteomics, metabolomics, and phenomics. These data are derived from diverse assays and experiments, spanning multiple spatial and temporal scales. While genomics has traditionally been a primary focus in personalized and precision medicine, other omics fields are increasingly contributing to a more comprehensive understanding of how an individual's complex biology influences their health. High-throughput multiomics technologies enable the collection of extensive and holistic biological data, whereas advanced computational tools facilitate high-dimensional data modeling, making analysis accessible and user-friendly.[18]

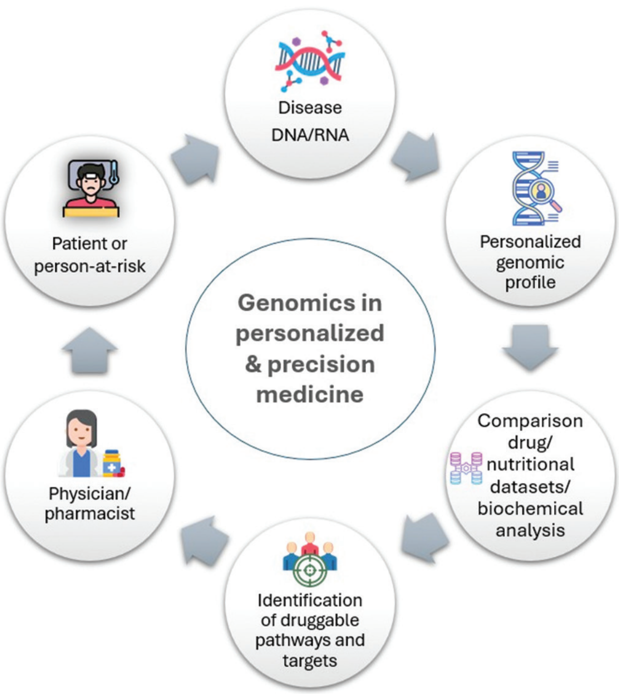

Figure 7. Genomics through the multipoint view of personalized and precision medicine. Genomics provides valuable biological insights, as it is a branch of life sciences focused on understanding and mapping genomes.

are used for various clinical conditions, such as inborn errors of metabolism, progress in expanding omics data has been limited. This hampers a deeper mechanistic understanding of cellular networks influenced by nutrition-driven gene expression and complete gene regulation. The main challenge lies in the clinical sector, which should integrate existing data, overcome the limitations of self-reported procedures in research, and make omics data, along with nutrigenetics and nutrigenomics research, widely accessible.[20,26-29]

We have only recently started to recognize specific gene–diet connections, as many clinical and molecular phenotypes, such as body mass index, are influenced by multiple genes. While nutrigenetics focuses on how genetic variations impact metabolism, nutrigenomics examines how nutrients (food compounds) affect gene activity, assessing how mutations affect the assimilation of metabolites. Recent advancements in genomics and PPM have led to a growing number of evidence-based applications with the potential to significantly reduce morbidity and mortality in millions of individuals.

In summary, it is important to note that, in contrast to general genomics-related achievements, nutritional genomics is still in its early stages compared with PPM. However, using genomics indicators and other clinical tools represents a practical application of this emerging technology. Meanwhile, advancements in genomics have led to the concept that a deeper understanding of individual characteristics, such as genotype, can enable more precise personalization of pharmaceutical and nutritional therapies. PN is customized based on an individual's specific genetic profile, lifestyle, and health objectives, in contrast to general dietary guidelines that offer broad recommendations for the population as a whole[30] (Figure 8).

It is crucial to recognize that current PN approaches have achieved only limited scientific success in improving dietary habits or addressing diet-related health conditions. These strategies often target narrow population subgroups, limiting their broader impact on public health. To overcome this, a more holistic approach is needed—one that integrates biomedical and dietary assessments with psychobehavioral insights and innovative digital and diagnostic technologies for comprehensive data collection. An adaptive PN counseling system addresses this need by combining biomedical and health phenotyping, stable and dynamic behavioral indicators, and contextual food environment data. This integration utilizes advanced digital tools, including sensors and AI-driven methods. Such a system holds significant promise for transforming individualized nutrition strategies into scalable, accessible

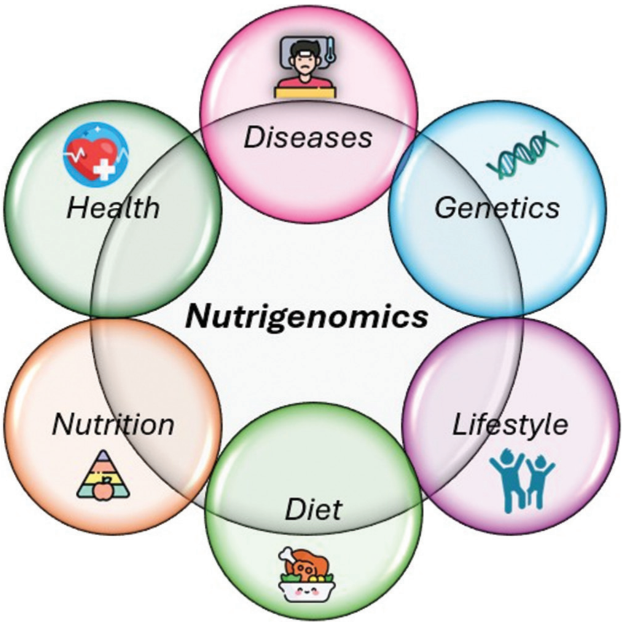

Figure 8. The evolution of personalized nutrition. Several omics factors can influence an individual's response to diet and its impact on health. The emergence of new nutritional biomarkers, which integrate information on intake and its effects on the organism, has generated interest, especially regarding their relationship with health and disease. Omics technologies play a crucial role in exploring these connections. At its core, personalized and precision medicine represents the intersection of individuals, their environment, and the evolving markers of health and disease, along with the social and behavioral factors that shape outcomes over time. This includes (i) people: Patients, individuals at risk, and populations served; (ii) markers: Indicators of health and illness, encompassing genetics, genomics, metabolomics, phenomics, pharmacogenomics, and other omics platforms; (iii) exposome: Environmental exposures and influences, both internal (e.g., microbiome and gut–brain interactions) and external (e.g., socioeconomic factors, food quality, agriculture, and geographical influences); and (iv) behavioral health: Factors such as exercise, self-care, addiction, anxiety, and lifestyle choices that impact individuals and populations. Together, these elements form the foundation for understanding health and disease through a personalized, multidimensional approach.[31]

solutions that deliver meaningful health benefits to a large population.[32]

It is essential to consider both ends of the spectrum—nutrigenomics and deep phenotyping—while accounting for multiple factors when designing personalized and unbiased nutritional solutions for individuals or specific population subgroups. In addition, a collaborative effort between basic scientists, clinical researchers, and health-care professionals is essential to create a comprehensive foundation that enables the successful implementation of these novel insights at the population level. This study explores the latest advancements in analyzing and monitoring dietary habits, food behaviors, and deep phenotyping. In addition, we highlight the relevance of emerging applications in conjunction with nutrigenomics, proteomics, and metabolomics.

Today, genomics-driven PN accounts for almost all relevant environmental influences throughout life on human health conditions. The latest advancements show that genetic variation affects connections between nutrients and the genome, which may alter disease risk. While there are food products that cater to the needs or preferences of specific consumer groups, these choices are mainly driven by empirical consumer science rather than by nutrigenomics and nutritional approaches. This understanding helps elucidate human variability in dietary preferences, requirements, and responses, paving the way for future scientific tools for consumption assessment, guided by PN-based advice for health maintenance and disease prevention.[33]

2.2. Proteomics

As mentioned previously, systems biology integrates multidisciplinary scientific approaches to predict and describe the dynamic properties of living biosystems, which are understood as complex signaling networks. In the realm of nutritional sciences, systems analysis of both standard and nutrient-modified signaling networks, along with an understanding of underlying genetic polymorphisms, is expected to pave the way for a future where individual health is enhanced through predictive and preventive nutrition.[34]

The advancement of omics technologies has provided effective methods for a thorough and targeted study of biological systems, leading to more precise diagnostic tools and the development of targeted treatments. Advances in proteomics technology allow for the simultaneous identification and quantification of the expression profiles of thousands of proteins. Proteomic analysis has emerged as a powerful technique for describing the patients' molecular profiles, allowing analysis of tissue and bodily fluids.

Proteomics plays a critical role in discovering novel biomarkers for disease diagnosis, prognosis, and therapeutic strategies. Identifying and quantifying proteins provides crucial data about disease conditions and how they respond to treatment. More broadly, proteomics can uncover the molecular mechanisms critical for an organism's adaptation to its ecological niche.[35] In this context, proteomics involves the large-scale study of proteins, focusing on their structures, functions, and roles in living organisms. As such, proteomics is increasingly used to explore both health and disease, as well as to address issues related to food quality, safety, bioactivity, and to develop healthier food products.

The goal of clinical proteomics is to identify and quantify proteins in clinical samples such as blood, urine, or tissue, with the aim of gaining insights into disease mechanisms, discovering biomarkers for disease, and pinpointing potential therapeutic targets for disease prevention[36-38] (Figure 9).

Nutritional proteomics (Figure 10), also known as nutriproteomics, leverages proteomic tools to analyze molecular and cellular changes in protein expression and function while assessing how proteins interact with food nutrients.[41] It is essential to recognize that proteins specific to an organ, once released from damaged tissue, often undergo degradation upon entering the bloodstream. In addition, blood serum contains many proteins, including albumin, which has a broad dynamic range, making accurate quantification challenging. Variations in serum protein levels can reflect shifts in the inflammatory response, offering insights into the underlying pathological process. Therefore, collecting organ-specific fluids such as synovial fluid, urine, or spinal fluid near the affected tissue may provide a more reliable source of potential diagnostic and therapeutic biomarkers than serum. Protein profiles have been shown to serve as valuable markers, capable of predicting treatment outcomes for various diseases, including nutritional disorders. The standardization of methodologies and integration of proteomic data into publicly accessible databases are beginning to address these challenges. With these advancements, the era of personalized, patient-tailored therapeutic strategies is approaching. As a result, clinical and nutritional proteomics seek to apply the methodologies and principles to the fields of PPM and PPM-guided PN and PF.[40]

Comprehensive protein profiles complement the genome by reflecting expression in specific cells or organs, plasma, or serum, enabling the identification of biomarkers that respond to dietary changes or treatment and potentially predicting biological processes. While proteomics has yet to be widely adopted in nutritional research, it offers advantages over transcriptome analysis, as it directly examines the molecules responsible for conducting biological functions.[42]

In the food industry, proteomics-based techniques play a critical role in ensuring food safety and authenticity. These methods are used to detect foodborne pathogens by analyzing variations in their proteome, identify allergens and toxins, validate and optimize food processing, and pinpoint bioactive compounds in functional foods. In addition, proteomics enables the authentication of meat and

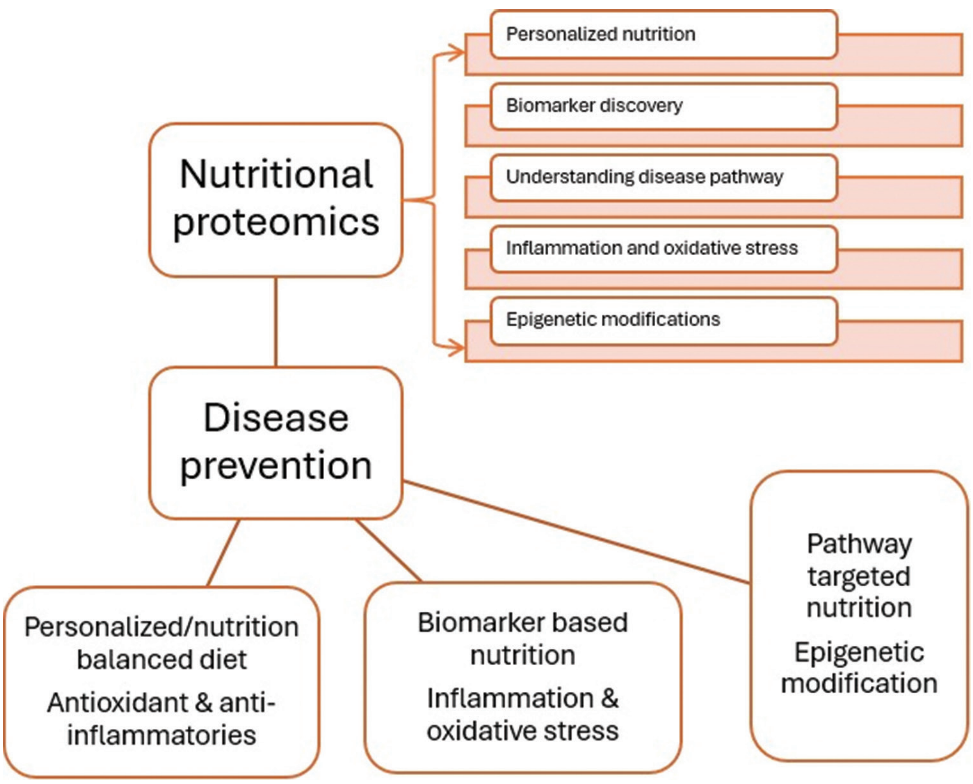

Figure 9. The intersection of nutritional proteomics and disease prevention. Personalized nutrition is a powerful tool that enables consumers to improve their dietary habits, optimize health, and prevent diet-related diseases. Omics technologies provide detailed insights into metabolic dynamics. However, translating these insights into personalized, simple, and affordable nutrition protocols remains challenging due to the complexity of metabolism and technical and economic limitations. Proteomics is essential to identify proteins that serve as biomarkers associated with disease progression.[38,39]

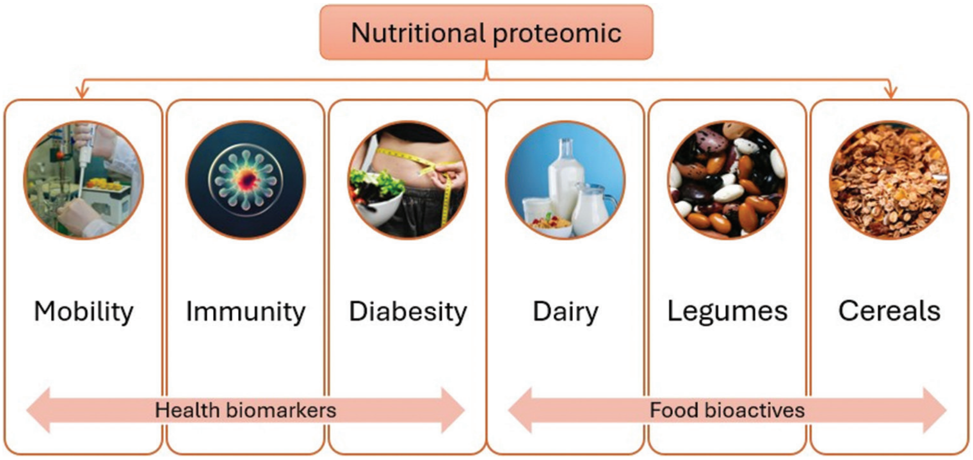

Figure 10. Nutritional proteomics (nutriproteomics) focuses on two key outcomes: (i) Identifying health-related biomarkers and (ii) studying food bioactives, along with their applications. The emerging field of nutriproteomics, which holds great promise in nutrition science, builds upon nutrigenomics and nutrigenetics while serving as a complementary approach. It plays a crucial role in molecular nutrition research and personalized nutrition by achieving two main objectives: (i) Analyzing and quantifying bioactive proteins and peptides derived from food and (ii) identifying biomarkers that reveal mechanisms of action, efficacy, and potential side effects of nutritional interventions. Modern nutrition research aims to promote health, prevent disease, enhance performance, and evaluate risks and benefits. As a result, nutriproteomics must identify early pre-symptomatic biomarkers to detect subtle metabolic deviations, though a clear definition of "normal" metabolism remains lacking. From a molecular standpoint, nutriproteomics encompasses two key areas: (i) The discovery, quantification, and characterization of biomarkers and (ii) the analysis of bioactive compounds, with proteins playing a significant role in nearly all biological functions. These biomarkers must be integrated with genomic and genetic markers, as nutrition aims to optimize specific health aspects without negatively impacting others. Therefore, holistic and integrative approaches are essential. The advancement and effectiveness of proteomics in nutrition and health will depend on several critical factors, including study design, data generation, data processing, data correlation, genetic susceptibility, and epigenetics.[40]

dairy products by identifying species-specific biomarkers. With its broad application in food safety, nutrition, and related fields, proteomics holds great promise for the future. Moreover, by examining how different processing techniques affect food proteins, proteomics contributes to enhancing food quality and refining production processes.[43]

Nutriproteomics applies proteomic methods to nutrition research and practice. It also represents the interconnection of bioactive food ingredients with proteins through two basic approaches. The influence of nutrients on protein expression is assessed through protein mapping and by examining nutrient–protein interactions, including post-translational modifications and small-molecule binding. Integrating these insights with functional data from established biochemical and physiological methods enhances our understanding of how bioactive dietary components contribute to diet-related disorders, such as diabetes and obesity. These biomarkers serve as valuable tools for disease diagnosis and treatment, offering precise indicators of the efficacy and safety of specific nutrients.[37,41,42,44-48]

The field of nutrition research has been transformed by proteomics as a powerful discovery tool. Proteome analysis is a valuable tool for addressing key nutrition-related disorders.[49] When integrated with other advanced omics technologies and biological systems, proteomics can greatly enhance the identification of key proteins that regulate metabolic pathways. The synthesis, degradation, and modifications of these proteins are influenced by specific nutrients and dietary factors.[50] This innovative approach will accelerate our understanding of the intricate mechanisms governing nutrient utilization, including dietary efficiency, facilitate the identification of novel indicators for nutritional status and disease progression, and establish a framework for dietary prevention and intervention in disease. Therefore, proteomic analysis promises to improve human health and increase the efficiency of livestock farming.

The evolution of PPM relies on comprehensive and integrative approaches (e.g., proteomic technologies) to provide better patient care and valuable disease insights. This application of proteomic methods to diseases is known as clinical proteomics, a powerful tool that studies changes in disease pathways and identifies new protein biomarkers. A proteomic biomarker is a specific peptide or protein associated with a specific condition, such as the onset or progression of a disease or response to treatment, or a measurable characteristic that serves as an indicator of normal biological processes, pathogenic processes, or responses to therapeutic interventions.

Proteomics is thus becoming a powerful tool in the realm of PN and PF, offering insights into an individual's metabolic state, nutrient deficiencies, disease risk, and optimal dietary needs. As technology continues to advance, proteomics analysis will become increasingly feasible and affordable, paving the way for PN to become a standard approach to health care. Proteins and metabolites linked to dietary patterns may serve as prognostic markers, guiding future clinical interventions and aiding in the identification of intermediate phenotypes while also shedding light on the molecular mechanisms underlying diet-related disease. However, there is limited data on the proteomic and metabolomic signatures of healthy dietary patterns.

2.3. Metabolomics

Individuals have varying needs for and responses to nutrients and bioactive molecules in their diet. At the same time, biological systems are highly complex, with essential processes occurring at multiple molecular levels, including nucleic acids, proteins, and small molecules. In this context, metabolic heterogeneity is influenced by numerous factors, such as genetic and epigenetic variations, the microbiome, lifestyle, dietary intake, and environmental exposures.[3,51-54]

Metabolomics is the scientific study of chemical processes involving metabolites—small-molecule substrates, intermediates, and end products of cell metabolism found in tissues, cells, or biofluids. Unlike genomics, transcriptomics, or proteomics, which typically rely on a single instrument for measurements, metabolomics necessitates a diverse set of analytical tools.

Targeted metabolomics enables the identification of specific metabolites through comparison with established chemical parameters, facilitating the development of biomarkers and the testing of hypotheses. However, untargeted metabolomics focuses not on the characterization and quantification of compounds but rather on the identification and discovery-based research. It can identify and quantify bioactive compounds, but has both advantages and disadvantages.

Nutritional metabolomics is a powerful and precise approach for identifying and characterizing biochemical pathways. It provides deep insights into the complex interplay between dietary exposure and chronic diseases, shedding light on metabolic phenotypic changes and their underlying mechanisms. This method has four main applications in nutritional research:

(i) Identifying dietary biomarkers.
(ii) Characterizing diet-related diseases and disease biomarkers.
(iii) Utilizing PN to elucidate mechanisms underlying dietary interventions.
(iv) PN and PF.[54,55]

These areas primarily focus on understanding how dietary compounds and their metabolites affect the host over time after consumption. They also aim to find biomarkers related to diet and determine how the dose of phytochemicals influences the connection between diet and health. Furthermore, metabolites serve as crucial biological communication channels, offering a valuable functional readout at the intersection of various influential factors that shape health and disease (Figure 11).

In the field of food science and nutrition research, there is an increasing emphasis on quantitative metabolomics. Targeted quantitative metabolomics is extensively applied in food composition analysis, body fat index characterization, detection and monitoring of nutrient deficiencies and metabolic disorders, dietary intake assessment, and the formulation of dietary guidelines for the prevention and treatment of chronic diseases.[28,57] The application of PN and PF in metabolomics can generate valuable data for optimizing nutritional regimens, supporting optimal child growth, and enhancing the composition of commercial products. These are just a few areas where metabolomics is making an impact, contributing to the advancement of personalized and precise health care. With current knowledge, metabolomics can be integrated into routine clinical practice. Sensitive metabolomic biomarkers may be detected using cost-effective and accurate test strips,

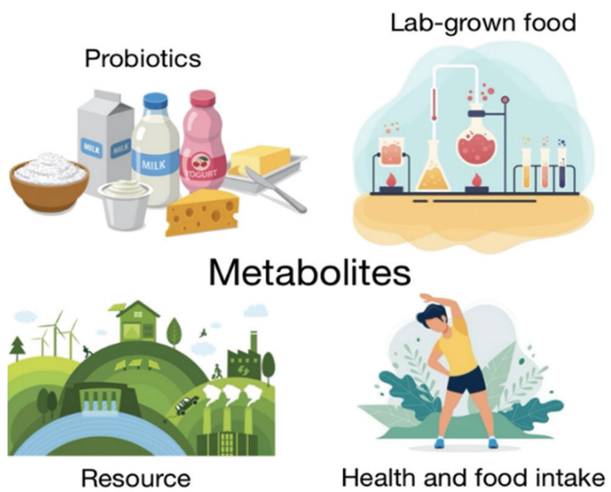

Figure 11. Metabolomics (food metabolome) via the phenotype of individuals and food. The food metabolome provides valuable insights into the relationships between metabolites, health, and nutritional status. It is a subset of the human metabolome, originating from the digestion and biotransformation of food and its components. While over 25,000 compounds have been identified in various foods, along with their metabolism by host enzymes and gut microbiota, the food metabolome remains highly complex, with its composition varying significantly based on dietary intake. This variability serves as a valuable and extensive data source for monitoring dietary exposure and identifying foods that influence disease risk.[54,56]

enabling rapid assessment of biofluids at the patient's bedside. This approach could improve diagnosis, treatment, and prognosis, paving the way for more personalized medicine.[31,58]

In this context, PN and PF are emerging branches of nutrition science that leverage omics technologies (e.g., genomics, proteomics, and metabolomics) to analyze individual responses to foods or specific dietary patterns. Their goal is to identify the most effective diet or lifestyle interventions for preventing or treating specific diseases. Metabolomics plays a fundamental role in nearly every aspect of PN and PF. It enables the comprehensive identification of thousands of compounds in foods, the detection of food byproducts in human biofluids or tissues, the assessment of nutrient deficiencies or excesses, the monitoring of biochemical responses to dietary interventions, and the evaluation of both short-term and long-term dietary habits. In addition, it aids in the development of targeted nutritional therapies. As a result, metabolomics is crucial to advancing nutritional science and making the implementation of PN and PF a reality.

In general, metabolic homeostasis is altered in critically ill patients. Maintaining homeostasis under continuously changing conditions is called phenotypic flexibility or systems flexibility. Under conditions of continuous energy overload, maintaining homeostasis has an adaptive cost. Adipose tissue stores excess energy. Nevertheless, when storage surpasses normal physiological limits, insulin resistance occurs, leading to complications such as ectopic adipose deposition in and around vital organs. This also causes elevated plasma glucose levels, which contribute to oxidative damage in the microvasculature and sustained low-grade inflammation caused by macrophage infiltration in adipose tissue.

A lack of phenotypic flexibility can lead to the development of pathologies or suboptimal health. However, pathology does not always emerge during the disease process or within the organ that loses flexibility. For instance, the inability of peripheral adipose tissue to effectively absorb glucose or convert it into fatty acids can result in the accumulation of lipids in the liver. This can also lead to insulin resistance in other organs, such as skeletal muscle and the liver. Factors that can trigger insulin resistance include poor nutrition, such as overnutrition or, in some cases, micronutrient deficiencies, and underlying diseases. In these situations, macronutrients and micronutrients act as key environmental factors influencing metabolite production through their effects on genetic regulation. In critically ill patients, where a comprehensive profile of circulating metabolites is analyzed, metabolomic studies consistently reveal that alterations in fatty acids, lipids, and tryptophan metabolite pathways are common and closely linked to disease states and outcomes.

To summarize, system flexibility plays a crucial role in health, disease, and potentially aging. However, interindividual variations arise from multiple factors and have diverse consequences. Systems flexibility integrates all interacting systems, each influenced by genetic components and environmental (exposomal) factors. Therefore, it is essential to not only observe and quantify individual parameters but also assess and intervene at the systemic level. Metabolomics examines shifts in an organism's metabolic state due to factors such as drug treatment, environmental influences, nutrition, genetic variations, toxins, and diseases. This is achieved by globally or comprehensively identifying and quantifying metabolites within biological systems.

Given the strong association between nutrition and most chronic diseases, nutritional metabolomics holds significant promise for elucidating the relationships among disease, nutritional status, nutrient intake, and diet. This approach involves examining the metabolic effects of specific diets to enhance overall health and advance personalized health care. Recently, nutritional metabolomics research has focused on investigating metabolic pathways and biomarkers associated with nutrition and their interactions with various diseases, considering both individual and population levels. The goal is to pave the way for personalized health care in the future. Integrating metabolomic profiling with transcriptional and genomic analyses provides valuable insights into nutrient deficiency and supply mechanisms, highlighting their impact on cellular homeostasis during critical illness and recovery.

Given metabolism's central role in nutrition, metabolomics is emerging as a vital analytical tool in human nutritional research. As a result, nutritionists are increasingly incorporating metabolomics into their study designs. However, despite its growing significance, the potential of nutritional metabolomics, also known as nutrimetabolomics, to shape health policies has yet to be fully realized.[59,60] Achieving this requires collaboration within the research community to leverage the opportunities that nutritional metabolomics presents. The application of metabolomics across multiple fields of nutritional and food science research greatly enhances our understanding of chemical compounds in food. When combined with other omics technologies, metabolomics and its analytical tools play a crucial role in assessing diet-related health changes. This makes it an essential component in the development of evidence-based dietary guidelines.[54,57,61-63]

2.4. Microbiomics and PN

The large-scale dynamics of the microbiome can be analyzed using many of the same tools and principles applied in population ecology. Understanding the metagenome and its collective genetic information provides valuable insights into the functional properties of microbial communities. Both the microbiome and metagenome are likely to play significant roles in health and disease, making their study a key frontier in human genetics. Growing evidence highlights the impact of diet and other microenvironmental factors in shaping the composition and metabolic function of the human gut microbiota, which can significantly affect overall health.

Human endomicrobiota and gut microbiota profiles are of great interest in dietetic interventions for assessing the consequences of diet on gut microbiome diversity. Molecular technologies provide valuable insights into the complexity and diversity of gut microbial communities both within and across individuals. Dietary intake, especially macronutrients, plays a crucial role in shaping the composition and functions of these intricate populations. However, the effects of dietary fats and proteins on gut microbiota remain poorly defined. Short- and long-term dietary modifications can influence microbial profiles, and early-life nutrition can have lasting effects by modulating the immune system through microbial interactions. The influence of environmental factors, including lifestyle, on the gut microbiota is still not well understood.[50,64,65]

The primary goal is to customize nutritional interventions by enhancing the richness and diversity of the gut microbiota. Diet plays an essential role in shaping microbiota, serving both as an influencer and as a substrate. As food is processed by gut microbes, it generates small molecules that facilitate interactions between the host and microbiome. For example, microbiota-derived short-chain fatty acids are absorbed by the host, significantly contributing to overall nutrition.[66-71]

While long-term dietary habits influence the composition and activity of the trillions of microorganisms residing in the human gut, the speed and consistency of the gut microbiota's response to short-term macronutrient changes remain unclear.[72,73] Translating microbiota research into clinical applications for nutritional interventions presents challenges. However, advancements in analytical and computational approaches are helping to bridge these gaps. Integrating microbiota studies with other omics technologies, such as proteomics and metabolomics, enables the development of more precise functional profiles.[74-77] Furthermore, controlled studies are essential to identify diet-independent environmental factors that play a crucial role in shaping the gut microbiota ecosystem. Addressing these factors will open new avenues for designing personalized nutritional strategies, driving the advancement of PPM-guided nutrition.[78]

2.5. Interactomics

Proper nutrition plays a significant role in disease prevention, making nutritional interventions essential strategies within the framework of PPM. The emergence of nutrigenomics and nutriproteomics stems from the integration of nutrition, genomics, and proteomics, shaping the future of PPM-driven health care. In this sense, interactomics—a discipline at the intersection of bioinformatics and biology—focuses on studying molecular interactions within a cell, particularly between proteins and other molecules, as well as their functional effects. The goal of interactomics is to analyze and compare interaction networks (interactomes) both within and across species, identifying patterns of stability or change in these networks. From a computational biology perspective, an interactome network is modeled as a graph or system that maps key interactions essential for maintaining normal physiological functions in cells or organisms.[79-84]

Interactomics—as a rapidly advancing field within systems biology—and network biology are now positioned to intersect with PPM-guided personalized therapy. This integration combines traditional clinical records and non-invasive, advanced cardiac imaging tools with epigenetic information and deep learning techniques for comprehensive molecular phenotyping of CHD. This innovative approach holds the potential to discover new drugs from natural compounds, such as polyphenols and folic acid, and repurpose existing drugs such as statins and metformin. Several clinical trials have explored the use of interactomics-sensitive drugs in both primary and secondary prevention. Interactomics and network medicine apply network science methodologies to study disease pathogenesis. Various analytical techniques, including protein–protein interaction (PPI) networks, correlation-based networks, gene regulatory networks, and Bayesian networks, have been employed to identify and analyze key molecular networks involved in disease.

Proteins are crucial in most biological processes, and their interactions are essential for regulating biological functions. The development of large-scale PPI screening techniques, particularly high-throughput affinity capture coupled with mass spectrometry and yeast two-hybrid analysis, has generated vast amounts of PPI data and more complex, comprehensive interactomes.[85] Interactomics and network medicine leverage these integrated approaches to analyze big omics data—encompassing genetics, epigenetics, transcriptomics, metabolomics, and proteomics—using computational biology tools. This combination has the potential to advance the diagnosis, prognosis, and treatment of complex diseases. However, several key challenges remain in interactomics and network medicine, including the incompleteness of the molecular interactome, difficulties in recognizing critical genes within genetic association regions, and the limited application of these approaches to human diseases.

3. Advances in food analytics and digitalization in PN and PF

Food analysis is an evolving field that focuses on the development of more robust, efficient, and sensitive analytical techniques. To achieve these goals, information technologies (IT) such as AI and ML, along with advanced computational resources, are employed to process and extract data (e.g., gathering dietary information) and to integrate model features for generating outputs that elucidate the complex relationship within large-scale "Big Data" datasets, which encompass numerous data points and variables (Figure 12).

Recent advances have led to significant developments in novel techniques in the following areas:

(i). Molecular methods and DNA-based techniques now enable faster and more precise detection of bacteria in foods, characterization of microbial communities, and identification of genetically engineered crops, all of which remain critical areas of investigation.

(ii). Biosensors are analytical devices composed of a specific biologically recognized element, such as enzymes, antibodies, or microbes, paired with a transducer that converts a biochemical response into an electrical signal. These devices are used to detect food components, including preservatives, colorants, and sweeteners, as well as contaminants such as toxins, pesticides, antibiotics, hormones, and microbes.

(iii). The development of advanced methodologies has led to the application of peptide nucleic acid-based technologies for food authentication and analysis, the refinement of immunoassay techniques to detect veterinary drug residues in food products, and the enhancement of methods for characterizing plant food allergens.[86] Figure 13 provides a comprehensive overview of the components and activities that constitute a fully integrated and PN service.

Figure 13 provides a comprehensive overview of the key elements and activities that constitute a PN-guided service. Specifically, it illustrates the process from utilizing various technologies for data collection, as previously discussed, to processing this information through big data analytics, algorithms, and AI to generate PN advice. In addition, it highlights the importance of providing consumer feedback and establishing a continuous support system to monitor progress and encourage behavior changes that promote positive health outcomes. Meanwhile, digitalization can facilitate the adoption of PN and PF through the following means:

(i). Data collection and analysis: Digital tools and platforms allow users to gather and track their health-related data, such as blood sugar levels, cholesterol, lipid profiles, and nutritional and dietary biomarkers, through wearables, mobile applications, and genetic testing. Advancements in profiling algorithms enable the rapid management of vast amounts of data and the identification of patterns and correlations.

(ii). Personalized meal planning: Digital platforms can generate and recommend customized meal plans based on an individual's dietary preferences, genetics, allergies, nutritional requirements, and health

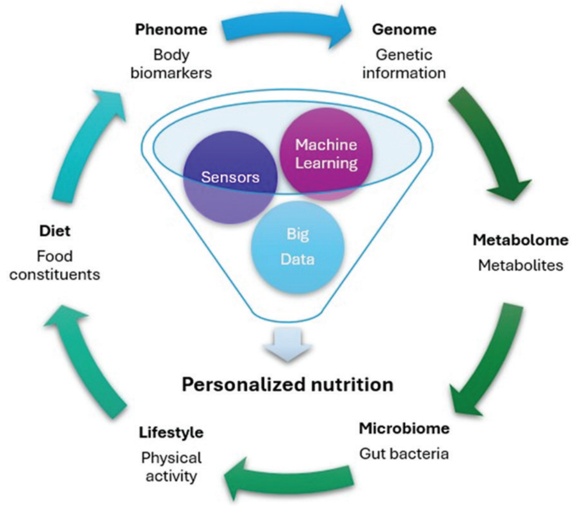

Figure 12. Big data analytics in personalized nutrition (PN) involves the genome, metabolome, microbiome, lifestyle, diet, and phenome. Nutrition plays a key role in our overall well-being, influencing both physical and mental health. As understanding of the intricate relationship between diet and health advances, PN has emerged as a promising strategy to optimize individual dietary choices. This approach involves customizing dietary recommendations based on unique characteristics such as genetics, metabolism, lifestyle, and health goals. By adjusting the diet to meet specific needs, PN can aid in managing chronic conditions, boosting the immune system, improving energy levels, and lowering the risk of diet-related diseases. Although the integration of digital technologies has facilitated technical advancements and the broader adoption of PN, challenges and ethical concerns remain, such as data privacy, algorithmic accuracy, and potential biases in data analysis. PN leverages the latest advancements in analytical instrumentation (e.g., omics) and computational tools (e.g., big data and AI) to gain deeper insights into the connections between foods, individuals, and health. This knowledge is then applied to the design of foods tailored to specific nutritional needs, ultimately promoting better health and well-being.[9]

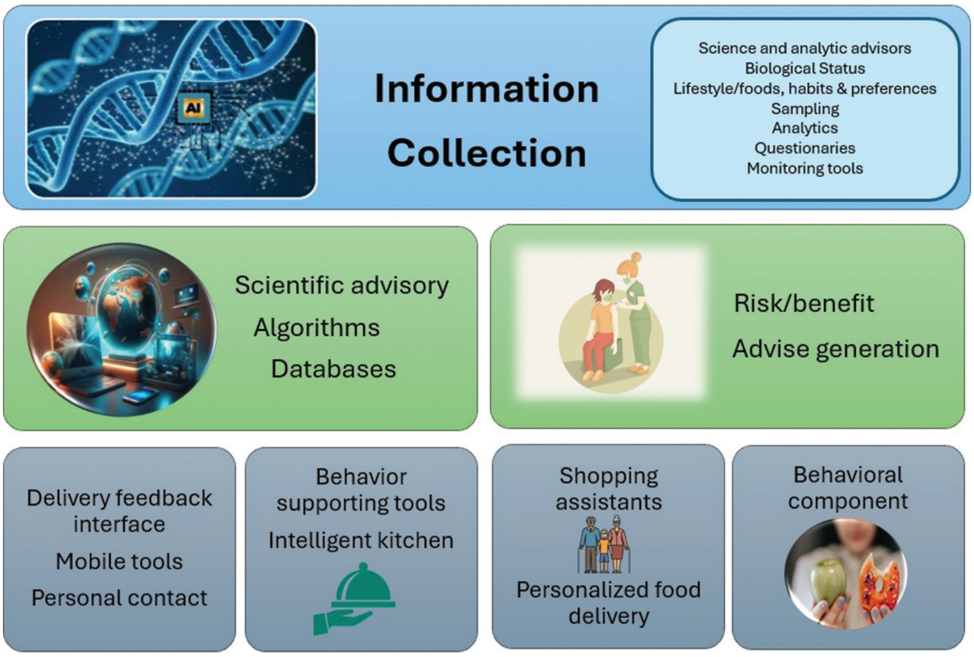

Figure 13. Overview of the elements and activities that constitute a fully integrated personalized nutrition (PN) service. PN is rapidly gaining traction as an innovative approach to guiding individuals toward informed dietary choices. It is built on two fundamental pillars: (i) The scientific, analytical, and technological components that ensure the accuracy and effectiveness of nutritional recommendations, and (ii) the equally vital behavioral dimension that ensures these recommendations are practical and actionable. While the growing interest in PN aligns with strong societal trends, delivering such a service will require innovative strategies beyond those currently employed by traditional nutrition and health-care sector stakeholders. It is likely that a new ecosystem of interconnected companies will emerge to meet this evolving demand. By shaping food choices, PN has the potential to exert a profound influence on the food supply chain and on the way information about ingredients and products is communicated to consumers.[87]

objectives. These plans may include detailed recipes and portion sizes tailored to the individual.

(iii). Behavioral tracking: PN tools assist users in monitoring their progress toward defined health goals, providing feedback and recommendations to enhance motivation and adherence.

(iv). Remote coaching and support: Digitalization enables individuals to interact remotely with nutritionists, dietitians, and other health professionals. Through video consultations and messaging, individuals can obtain PN advice and support without the need for in-person visits, making the overall process more convenient.

(v). Integration with e-commerce: Digital platforms can connect health-conscious users with PN products and supplements available on e-commerce sites, making it more convenient to follow their customized dietary plans.

Digitalization plays a significant role in addressing challenges by leveraging technology to analyze health data, disseminating knowledge and awareness related to PN and PF, and facilitating remote consultations with nutrition experts. As digitalization stakeholders continue to expand into this domain, the PN market is expected to experience further disruptions and cross-industry collaborations (Figure 14).

As shown in Figure 14, the potential market for PN is huge. Most commercial PN-driven interventions are delivered directly to consumers by online platforms. The public shows a strong interest in receiving PN guidance; however, concerns regarding the reliability of certain primary care service providers, the credibility of information sources, and the security of personal data remain. Other influencing factors include individuals' preferences for primary care services and their diverse socioeconomic backgrounds. In this regard, direct-to-consumer DNA testing serves as an example of primary care services available to the public.[89-91] In this context, guiding principles should be applied when designing and implementing PN research, considering its multidisciplinary nature.[92] Designers, researchers, and dietitians should collaborate to conduct a thorough review of PN research, utilizing a standardized definition to guide the development of future NP-driven practices. This effort should also address challenges arising from rapid technological advancement and the lack of consensus on integrating these tools into clinical settings. Establishing stakeholder consensus on standardized methods for implementing multiomics technologies and IT-assisted support could accelerate their adoption in clinical practice, enhancing NP-based recommendations for disease prevention and treatment. When vital research

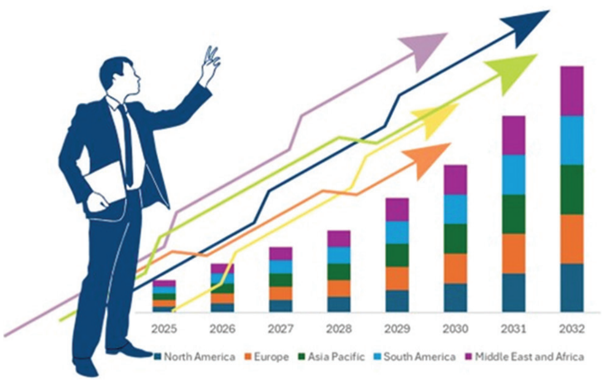

Figure 14. Global personalized nutrition (PN) market. The global PN market is expected to reach USD 20.14 billion by 2029. Dietitians worldwide have been incorporating PN into their practice since the concept was first introduced. This approach delivers tailored nutritional guidance based on an individual's physical, emotional, and clinical needs, considering factors such as genetic makeup, physical activity, microbiome composition, eating habits, and sleep patterns. The PN market is segmented by product type, age group, suppliers, dosage forms, end-users, and applications. Analyzing growth trends within these segments provides valuable market insights, helping identify key opportunities and support strategic decision-making. The PN market spans multiple regions, including North America (e.g., United States, Canada, and Mexico), Europe (e.g., Germany, Sweden, Poland, Denmark, Italy, the United Kingdom, France, Spain, the Netherlands, Belgium, Switzerland, Turkey, and Russia), Asia-Pacific (e.g., Japan, China, India, South Korea, Australia, New Zealand, Vietnam, Singapore, Malaysia, Thailand, Indonesia, and the Philippines), South America (e.g., Brazil and Argentina), and the Middle East and Africa (e.g., United Arab Emirates, Saudi Arabia, Oman, Qatar, Kuwait, and South Africa). North America leads the PN market, driven by growing consumer awareness of health and wellness. The Asia-Pacific region is projected to experience significant growth between 2022 and 2029, largely due to rising obesity rates and increasing demand for customized health solutions.[88]

and reviews are unified, progress can be achieved in the field of human health for NPs.

Diet is more than just the sum of its individual components, and food is not merely a collection of nutrients. Instead, the chemical, physical, and biological properties contribute to sensory, safety, and functional attributes that extend beyond basic nutrition. Foods with similar ingredients but different structures—such as pre-cooked versus cooked rice with distinct starch compositions or raw versus homogenized milk with varying fat globule sizes—exhibit differences in digestion, absorption, and metabolic responses. PF is an emerging discipline within food and nutrition that integrates high-throughput omics technologies to enhance human health, well-being, and nutritional knowledge. This field encompasses a wide range of research areas, including nutrigenomics, and aims to explore the mechanisms of bioactive food components in the body, quantify dietary biomarkers to assess health states, evaluate food quality and safety, and analyze the body's biological response to different dietary patterns.

Foodomics is recognized as a subdiscipline within the four major branches of omics, including genomics, proteomics, transcriptomics, and metabolomics. The emergence of genomics and proteomics in the 1990s was driven by the advent of high-throughput technologies for rapid DNA sequencing and mass spectrometry (MS)-based protein identification.[93] This technological progress led to the development of microarrays, enabling the rapid and comprehensive analysis of gene expression and giving rise to transcriptomics in the early 2000s. These advancements, in turn, facilitated the emergence of metabolomics.

Metabolomics employs high-throughput analytical chemistry techniques—such as liquid chromatography-MS, nuclear magnetic resonance, and gas chromatography-MS—to characterize the metabolome, the collection of small molecules involved in metabolism.[94] Although metabolomics is not as rapid or high-throughput as genomics or proteomics, it allows researchers to analyze hundreds or even thousands of metabolites simultaneously, rather than focusing on one or a few compounds.[86] This capability has led to several large-scale metabolomic projects aimed at identifying and mapping the metabolomes of microbes, plants, and humans. These studies typically employ liquid chromatography-MS, nuclear magnetic resonance, and gas chromatography-MS, or a combination of these techniques to quantify and profile metabolites in cells, tissues, and biofluids. In addition, more targeted metabolomic research has been conducted to explore the metabolic responses of humans to various foods and dietary components, such as soy, citrus fruits, nuts, meats, and tea, further advancing our understanding of the complex interactions between diet and metabolism.[95]

Metabolite levels are biologically significant because, similar to the canary in a coal mine, they are often the first to respond to both internal physiological changes and external environmental factors. This makes metabolites valuable for various purposes, including monitoring the body's immediate reactions to stimuli, developing biomarkers for early disease detection, and enhancing food safety. While there is clinical evidence supporting the establishment of a comprehensive and integrated framework for PPM-based nutritional interventions in clinical settings, this evidence is still limited. For example, interventional nutrition has enabled the implementation of specific diets that have saved patients and their families from severe outcomes. Genetic testing has helped to identify patients who are slow or fast metabolizers in the context of wellness. While genomics-based PN has been applied, PPM-based nutrition still faces challenges due to the lack of sufficient diagnostic tests for full integration into clinical practice. To be fully effective, PPM-based nutrition should be integrated into the daily diet to prevent and mitigate diseases commonly observed in metabolic disorders.

Digitalization has transformed PN and PF by empowering people to assume responsibility for their own health, access tailored guidance, and make informed choices for improved well-being. Digital tools can continually improve data accuracy, providing users with more reliable and valuable insights for making informed dietary choices. Technological advancements, particularly in multiomics and IT resources, have significantly propelled the field of PN. These innovations hold great promise in developing objective biomarkers for specific foods—through bioactive components—and nutrient intake, providing an effective complement to current self-reported dietary recall methods. Proper application of these guiding principles could pave the way for a standardized definition of PN and facilitate a consensus on how to implement these tools in clinical settings.

Nutrition experts and dietitians must not only grasp the fundamentals of these advancements but also stay informed about ongoing research to position themselves as leaders in delivering PN-guided therapies. Achieving this requires collaboration among a diverse group of professionals, including biodesigners, translational and clinical researchers, nutritionists, clinicians, nurses, bioinformaticians, statisticians, chemists, and other key stakeholders. The new frontier in nutritional sciences lies in our ability to predictably engineer physiological networks to optimize diet, health, and disease management. This multidisciplinary integration is essential for developing the knowledge needed to establish evidence-based PPM-based nutrition. Ultimately, this collaboration will enable more precise dietary interventions and improve health monitoring strategies.[96]

4. The future of PN in PPM

PN, an interdisciplinary field, examines how nutrients interact with the body to support health and well-being. In daily practice, PN provides tailored health advice regarding food intake and health goals, such as the guidance traditionally offered by doctors, dietitians, and nutritionists (Figure 15).

Nutrition is inherently complex, influenced by a wide range of internal and external factors. To fully understand and address this complexity, holistic and network-based approaches are needed to uncover the dynamic interactions within these systems across both temporal and spatial scales. Hence, the concept of PPM-based nutrition is to deliver precise nutritional recommendations personalized to each individual to promote a healthier lifestyle. An individual's integrative nutritional biomarker profile, combined with the characterization of specific food components, can determine their optimal PPM-based nutrition. Such advancements are driving the development of innovative strategies for managing chronic diseases. PPM-based nutrition holds significant potential for promoting health by incorporating comprehensive nutrigenomics analyses while accounting for an individual's genetic profile. Consequently, there is a growing need to identify novel nutritional biomarkers or biomarker patterns that connect diet with health, thereby enhancing our understanding of the role of nutrition in both health and disease.[98-100]

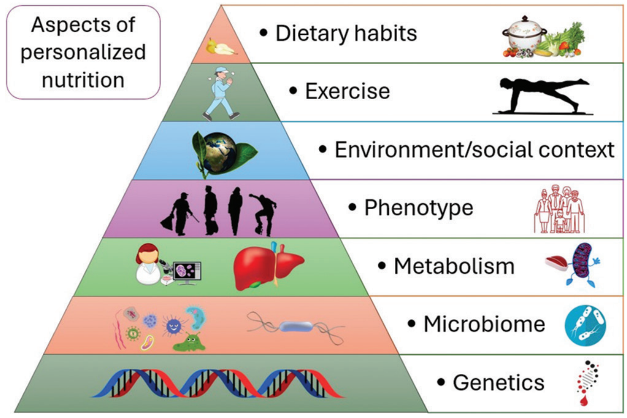

Figure 15. Personal input data elements of personalized nutrition (PN). In addition to phenotype data collected through questionnaires, tracking devices, and software applications, there is an increasing emphasis among providers on incorporating personal genetic or genomic information, including the genetic makeup of the gut microbiome. Efforts are currently underway to establish an internationally agreed-upon framework that defines the role of these scientific methods within PN. While a precise and uniform definition of PN is still lacking, the inclusion of genetic variants in personalized dietary recommendations is gaining support, despite limited scientific evidence supporting gene-based dietary guidance. This article aims to provide a science-based perspective on gene-based PN and weight management. Most studies conducted to date have found little or no clinical evidence supporting the effectiveness of gene-based PN. At present, gene-based nutrition is not applicable to the treatment of obesity. Nevertheless, personalized dietary recommendations based on an individual's genetic profile hold promise as an innovative approach for the prevention and treatment of obesity. Future human intervention studies are needed to establish the clinical validity of gene-based dietary recommendations.[97]

The foundation of PN is supported by several factors, including advancements in food analytics, the growing prevalence of nutrition-related diseases, the expansion of public health programs, and the increasing role of bioinformatics and mathematical modeling in nutrition science. In addition, the concept of gene–diet interaction and rising consumer demand for healthier food choices further drive this field forward. The rapid progress in omics technologies and related analytical techniques has significantly expanded their application in nutrition science. By generating high-throughput molecular data, omics enables a deeper understanding of the complexities of nutrition, fundamentally reshaping the field.

From both translational and clinical perspectives, staying informed about these emerging directions in nutritional science is essential for advancing health and disease management. By collecting individual data at the genetic, phenotypic, medical, and nutritional levels and using these data to provide personalized dietary recommendations, PN aims to maintain or improve health. Disease prevention and the treatment of existing conditions further enhance its effectiveness. Enhancing human health through PN has become a subject of significant interest. In this sense, multiomics can be leveraged to analyze the microbiota, metagenome, proteome, transcriptome, and metabolome, offering a detailed understanding of an individual's physiological state. As PN gains momentum, advancements in multiomics technologies are expected to shape future practice by facilitating the identification of objective nutritional biomarkers that link dietary intake with health status.[86]

The progress of PN will be driven by several key factors linked to the growing body of scientific evidence. First, establishing a robust theoretical framework that identifies the most relevant individual characteristics for PN is essential. Second, well-structured intervention studies must provide evidence of PN's effectiveness and cost-efficiency. Finally, implementing a regulatory framework will be crucial for safeguarding public interest and instilling confidence among health-care professionals and policymakers. Achieving these goals will require a significant expansion of scientific research in the field.[95]

In this new dietary era, marked by a societal shift from merely consuming what is available to making healthy and conscious decisions, rethinking and refining dietary habits has become increasingly important as we move toward PN tailored to individual needs. In addition, by leveraging advanced analytics, PN can deliver personalized dietary advice that accounts for each individual's unique characteristics, preferences, and health goals. This approach offers the potential to enhance overall health, support chronic disease management, and maximize athletic performance. As technology and research continue to advance, PN provides a new avenue for improving individual health and well-being.

The integration of PN with PF is evolving beyond a mere trend, driven by a new generation of consumers seeking clarity amid the confusion of mass-marketed, one-size-fits-all nutritional products. The fusion of technological advancements and growing consumer awareness of nutrition and wellness—along with greater access to relevant information—is driving the development of innovative health products and services tailored to individual needs. By leveraging online tools such as questionnaires, along with advanced data sources such as wearable devices, DNA analysis, blood biomarkers, and microbiome profiling, PN-driven approaches are advancing. These strategies enable the creation of products that are more precisely formulated to align with an individual's lifestyle, genomic predisposition, and metabolic requirements, surpassing anything currently available.

4.1. Food products enriched with autoprobiotics

It has been shown for the first time that exposure to probiotic preparations under conditions simulating space flight factors inherent in interplanetary expeditions (e.g., hypomagnetic environment, altered radiation background) does not lead to changes in their quality. Therefore, probiotics may be used in expeditions to the Moon, following recommendations established under terrestrial conditions. The use of food products enriched with autoprobiotics exerts an effective stabilizing effect on the human intestinal microbiota in experiments simulating the impact of space flight factors. Thus, food products enriched with autoprobiotics are considered promising for medical support during long-term, including interplanetary space flights. This work experimentally substantiates the development of food products incorporating autologous microorganisms, representatives of the protective intestinal microflora. The impact of a combination of altered environmental factors (e.g., radiation exposure, freezing, hypomagnetic environment) does not adversely affect the probiotic properties of individual cultures or their associations. These findings suggest that technologies for enriching food products with autoprobiotics may be applicable to future programs for deep space exploration.[101]

5. Conclusion

Human PN is a specialized branch of PPM that focuses on the biochemical connections between food and the human body. The shift from a healthy state to disease is influenced by variations in gene and protein expression, leading to the emergence of "omics sciences" as a critical field of study.

As discussed in the previous sections, significant progress has been made in PN due to a growing body of research supporting its effectiveness. Nonetheless, a deeper understanding of the complex interactions between genes and diet remains essential, especially as the development of novel food products further increases complexity.

The successful implementation of PN models in real-world settings is crucial for transforming theoretical concepts into practical applications. Challenges such as ethical considerations surrounding genomic data sharing, the high variability of multiomics data in biological samples, and the shortage of skilled professionals in big data generation, analysis, and management must be addressed to ensure the continued advancement of PN.

With advancements in omics techniques, the concept of food has evolved beyond being merely a source of energy, macronutrients, and micronutrients. It is now recognized as a key determinant of overall health and well-being.

The intricate relationship between micronutrients and gene expression plays a crucial role in various pathophysiological processes and offers valuable insights into disease prevention. Understanding these interactions can help delay the onset of chronic disorders, paving the way for more targeted and effective nutritional strategies.

Emerging technologies in omics-guided applications, such as nutrigenomics and deep phenotyping, have enabled the collection of extensive data on genetic markers, clinical indicators, precise body composition metrics, and dietary consumption. The complex interplay between genetics, dietary habits, and lifestyle influences an individual's risk of developing CVD. For instance, in cases of hypercholesterolemia, a key challenge lies in the misalignment between genes regulating lipid metabolism and the modern diet, compounded by various lifestyle factors. The primary challenge in both PN and PPM is effectively translating these insights into clinically actionable and relevant recommendations for improved health outcomes.

A deeper understanding of nutrient–gene–metabolite pathways will enable a more integrated approach to cellular studies at different levels. In this context, the interactions between gut microbiota and food should be thoroughly assessed. PN should focus on selecting the most appropriate foods for each individual, based on their effects on gene expression and gut microbiota composition. In addition to their primary function as an energy source, foods will increasingly be chosen for their bioactive components.

PN has the potential to revolutionize health-care by offering tailored meal plans and progress tracking, designed to align with an individual's unique characteristics and health goals. To fully grasp the integrated relationship between PN and health, it is essential to understand the underlying mechanisms governing systemic flexibility. Many of these mechanisms are influenced by PN, directly impacting health outcomes and overall well-being.

Following PN guidelines can significantly enhance disease management by focusing on diet-based biochemistry, insulin regulation, nutrient absorption, and nutritional tracking, ultimately leading to better health outcomes. The role of nutrients in regulating gene activity, both directly and indirectly, opens up new pathways for PN in the prevention and treatment of chronic health conditions.

We are entering an era defined by PN, PF, and molecular food design, which is reshaping our approach to health and wellness. This shift calls for the development of global scientific, clinical, social, and educational initiatives focused on PPM to foster this emerging branch. As we look to the future, digital advancements will propel PN-based therapies to new levels of accessibility, personalization, and precision. Technologies such as ML and big data analytics are set to revolutionize the medical nutrition sector, while their integration into wearable devices, mobile platforms, and smart devices will further enhance accessibility for patients.

In the coming years, the integration of PF, PN, systems biology, and general pathology will yield valuable insights into areas such as host–microbiome interactions, nutritional immunology, pathogen resistance in food microorganisms, and farm–animal production. This unified approach will also help us better understand post-harvest phenomena by linking genetic and environmental responses, ultimately identifying key bionetworks that influence health outcomes.

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