***Minireview Article***

**The Role of Omics Technologies in Pet Food Science: Advancing Nutrition, Health, and Safety**

**Abstract**

The integration of omics technologies, including genomics, transcriptomics, proteomics, metabolomics, and microbiomics, has revolutionized pet food science, providing deep insights into pet nutrition, metabolic health, gut microbiota composition, and disease prevention. These cutting-edge approaches enable the development of precision diets tailored to individual pets based on genetic predispositions, metabolic profiles, and gut microbiome interactions. This review explores the current applications of omics in pet food science, highlighting how these technologies aid in formulating functional pet foods, improving food safety, and enhancing overall pet well-being. Additionally, we discuss emerging computational tools, challenges in data integration, and future perspectives on multi-omics approaches, emphasizing their potential to revolutionize pet nutrition.

**Keywords:** Omics Technologies ; Gut Microbiome ; Metabolic Health; Food Safety

**1. Introduction**

The global pet food industry has seen remarkable growth in recent years, largely due to increased consumer awareness regarding pet nutrition and a shift toward science-backed, functional pet foods. As pets are increasingly considered family members, their health, longevity, and dietary needs have gained significant attention from both pet owners and the scientific community. According to market research, the global pet food industry was valued at $99.1 billion in 2022 [4] and is expected to surpass $135 billion by 2027 [6]. This expansion is driven by rising pet ownership, advancements in pet food formulations, and an increasing demand for high-quality, customized diets. The growth is also fueled by trends such as the humanization of pet food, sustainability in ingredient sourcing, and personalized pet nutrition [1]. The expansion of the natural pet food segment has led to a wide spectrum of products with different nutritional strategies applied across brands and introducing unique philosophies on what defines a natural pet food product [41,42]. Traditional pet food formulation has primarily been based on generalized macronutrient and micronutrient requirements, focusing on protein, fat, carbohydrates, vitamins, and minerals to ensure adequate pet nutrition. While this approach has effectively met the basic dietary needs, it fails to account for individual variations in genetics, metabolism, gut microbiome composition, and predisposition to diseases [2]. Recent advancements in omics sciences, including genomics, transcriptomics, proteomics, metabolomics, and microbiomics—have revolutionized pet nutrition research, providing a systems-level approach to understanding how diet influences pet health. These insights have paved the way for precision pet nutrition, in which diets are formulated based on an individual pet’s genetic profile, metabolic state, and gut microbiota composition. Omics-based research enables scientists and pet food manufacturers to optimize ingredient selection, enhance food functionality, and improve food safety protocols, ensuring that pet food formulations are not only nutritionally adequate but also tailored to specific health conditions, breed requirements, and life stages [3]. For example, genomics research has uncovered breed-specific nutritional needs, such as the propensity of Labrador Retrievers to develop obesity due to mutations in the POMC gene, which affects appetite regulation. Similarly, transcriptomics studies have shown that omega-3 fatty acids can regulate gene expression related to inflammation, highlighting their potential role in preventing joint diseases in ageing pets. Additionally, metabolomics has been instrumental in identifying biomarkers for metabolic diseases, such as diabetes, obesity, and kidney disease, allowing for early detection and dietary interventions [5]. Microbiomics research has demonstrated that gut microbiota composition significantly influences digestion, immune function, and even behaviour, reinforcing the importance of probiotics and prebiotics in pet diets. By integrating data from multiple omics disciplines, researchers can design targeted dietary interventions that support gut health, immune function, and chronic disease prevention [7]. For example, the combination of multi-omics analysis and machine learning algorithms has allowed for the development of precision nutrition plans that match an individual pet’s genetic and metabolic profile, much like the emerging field of personalized human nutrition [8].

Key Objectives of This Review

This review aims to:

Explain the role of omics technologies in pet food formulation and how they contribute to precision pet nutrition.

Discuss the applications of genomics, transcriptomics, proteomics, metabolomics, and microbiomics in advancing pet food science.

Highlight the impact of multi-omics integration on pet health and nutrition.

Address challenges in applying omics technologies, including data complexity, cost, and the need for species-specific databases.

Explore future directions and technological advancements, such as AI-driven data analytics and real-time omics monitoring.

**2. Omics Technologies in Pet Food Science**

Omics technologies have dramatically transformed the landscape of pet food science by providing a systems-level approach to understanding biological processes. These advanced technologies allow for a deeper exploration of the molecular, genetic, and metabolic pathways that govern health and nutrition in pets [9]. Unlike traditional approaches, which typically rely on general dietary recommendations based on species or breed, omics-based nutrition offers the ability to tailor diets that align with an individual pet's unique genetic, metabolic, and microbiome profiles [10,11]. This level of personalization has the potential to optimize pet health, address specific health conditions, and improve the overall efficacy of pet food formulations. Through the integration of multiple omics disciplines—including genomics, transcriptomics, proteomics, metabolomics, and microbiomics—scientists can investigate the complex interactions between an animal's genome, gene expression, protein function, metabolic pathways, and gut microbiota [12]. This comprehensive approach to nutrition considers the individual needs of pets at the molecular level, providing valuable insights into how specific dietary components impact their health. For instance, by understanding how genetic variations affect nutrient metabolism and digestion, researchers can identify breed-specific dietary needs, such as the increased requirement for certain amino acids in specific breeds or the reduced ability to metabolize particular nutrients [13]. Moreover, omics technologies enable the detection and correction of metabolic imbalances that may lead to common health issues such as obesity, diabetes, gastrointestinal disorders, and allergies. By examining how different ingredients and nutrients affect pet metabolism at a cellular and molecular level, researchers can design diets that optimize nutrient absorption and balance metabolic processes [14]. For example, metabolomic profiling may reveal specific biomarkers that signal an imbalance in lipid or carbohydrate metabolism, allowing pet food manufacturers to adjust the nutrient composition to prevent or manage conditions like obesity or diabetes [15].

Another critical application of omics research in pet food science is the optimization of ingredient composition for enhanced digestibility and nutrient absorption. By utilizing proteomics and metabolomics, scientists can examine how specific protein sources are digested and utilized by pets, ensuring that the chosen ingredients provide optimal nutrition [13,11]. Furthermore, omics allow for the identification of the most bioavailable nutrients in pet food ingredients, which helps improve the efficiency of nutrient absorption and ensures that pets receive the full benefits of their diet. In addition to improving nutritional quality, omics technologies play a crucial role in ensuring food safety. With the ability to analyze the molecular composition of pet food formulations, researchers can detect potential contaminants, allergens, and harmful microorganisms that may pose a risk to pets' health. For instance, microbiomics enables the identification of harmful bacteria or fungi in pet food ingredients, while metabolomics can help detect the presence of toxins or harmful by-products that may form during food processing [15.16]. This level of precision in food safety monitoring is essential for preventing health risks associated with contamination or poor-quality ingredients, thereby ensuring that pet food is not only nutritionally balanced but also free from harmful substances. The applications of omics technologies are transforming pet food science by allowing for the development of precision diets that cater to an individual pet’s unique nutritional needs, breed-specific predispositions, and health conditions [43]. By leveraging the power of genomics, proteomics, metabolomics, transcriptomics, and microbiomics, researchers are paving the way for more effective, safer, and customized pet food formulations that improve health, longevity, and quality of life for pets worldwide. Omics technologies have revolutionized pet food science by providing a comprehensive and systems-level understanding of biological processes, enabling researchers to formulate diets that align with individual genetic, metabolic, and microbiome profiles[17,18]. Unlike traditional approaches that focus on general dietary recommendations, omics-based nutrition considers the intricate interactions between an animal’s genome, transcriptome, proteome, metabolome, and microbiome. By integrating these disciplines, scientists can develop precision diets tailored to an individual pet’s unique nutritional needs, breed-specific predispositions, and health conditions.

Omics technologies allow researchers to identify breed-specific nutritional requirements, detect metabolic imbalances, and optimize ingredient composition for enhanced digestibility and absorption. Furthermore, omics research plays a crucial role in food safety, enabling the detection of contaminants, allergens, and harmful microbiota in pet food formulations. The following subsections describe the key omics disciplines and their applications in pet food science.

**Table 1: Summary of Omics Technologies in Pet Food Science**

| Omics Technology | Description | Applications in Pet Food Science |
| --- | --- | --- |
| Genomics | Study of the complete DNA sequence of an organism | Identifying genetic markers for nutrient metabolism, breed-specific diets, and disease susceptibility |
| Transcriptomics | Analysis of RNA transcripts to study gene expression | Understanding how diet influences gene expression and nutrient absorption |
| Proteomics | Large-scale study of proteins and their functions | Identifying bioactive peptides, assessing food quality, and detecting allergens |
| Metabolomics | Comprehensive analysis of metabolites within biological systems | Identifying biomarkers for metabolic health, obesity, diabetes, and kidney disease |
| Microbiomics | Study of microbial communities and their metabolic functions | Investigating diet-microbiome interactions, digestion, immunity, and behaviour |

**2.1 Genomics: Unlocking Genetic Potential for Precision Nutrition**

Genomics, the study of an organism's complete set of DNA, plays a foundational role in advancing pet food science by providing profound insights into how genetic variations influence key aspects of nutrient metabolism, food sensitivities, and disease predisposition. By analyzing the genetic makeup of different pets, researchers can identify the underlying genetic factors that shape how animals process and respond to various dietary components [19]. Through genetic sequencing and gene mapping technologies, scientists can uncover breed-specific dietary needs and tailor pet food formulations to optimize macronutrient balance and address specific health concerns. This personalized approach to nutrition can have a significant impact on both the prevention and management of common health conditions in pets, promoting long-term well-being and reducing the risk of chronic diseases [20]. A key application of genomics in pet food science is identifying genetic predispositions to certain health conditions, particularly those that vary between breeds. For example, research has revealed that Labrador Retrievers carry a genetic mutation in the POMC (pro-opiomelanocortin) gene, which is involved in appetite regulation. This mutation impairs the regulation of hunger signals, making Labradors more prone to overeating and, consequently, obesity. By understanding this genetic predisposition, pet food manufacturers can develop diets that are specifically designed to support weight management in Labradors, possibly through controlled levels of calories, increased fiber content, and nutrients that promote satiety [21]. These formulations could help mitigate obesity risks in this breed, ultimately supporting better overall health. Similarly, breeds such as the Alaskan Husky have evolved genetic adaptations that enhance their ability to metabolize fats, enabling them to efficiently process high-fat, high-energy diets, which are essential for their survival in harsh Arctic environments. Through genomic analysis, researchers have identified specific genetic markers that allow these dogs to thrive on high-fat, high-protein diets, which fuel their endurance and energy needs during activities like sledding. Understanding these genetic adaptations is crucial for formulating diets that align with the unique metabolic needs of Alaskan Huskies and similar breeds. Tailored high-fat diets can enhance energy production, improve performance, and support overall health, ensuring that these dogs maintain optimal body weight and energy levels throughout their active lifestyles [22]. Beyond individual breeds, genomics also aids in understanding genetic variations related to food sensitivities, allergies, and intolerances that can affect pets' ability to digest certain ingredients. For example, some breeds, like Bulldogs and Boxers, are more prone to food sensitivities due to genetic factors affecting the gut and immune system. Genomic analysis can identify specific genes responsible for these sensitivities, enabling the development of hypoallergenic pet foods or diets that are more easily digestible for these animals. This ensures that pets with these genetic predispositions receive the right nutrients without triggering allergic reactions or gastrointestinal distress. Additionally, genomic data can provide valuable insights into disease predispositions within various breeds. Certain breeds may be genetically predisposed to conditions such as heart disease, joint problems, or kidney issues [23]. By understanding the genetic markers linked to these diseases, researchers can recommend dietary interventions that may help prevent or manage these conditions. For instance, diets rich in omega-3 fatty acids may benefit breeds at risk for heart disease, while breeds predisposed to joint problems may benefit from diets enhanced with glucosamine and chondroitin. Incorporating genomic data into the development of pet food formulations is a powerful tool for preventing and managing breed-specific health issues [24]. By leveraging genomic research, pet food manufacturers can create precise, customized diets that cater to the unique genetic makeup of each breed, ultimately supporting optimal nutrition, health, and longevity for pets. The ongoing

advancements in genomics will continue to shape the future of pet food science, ensuring that pets receive nutrition that is both scientifically backed and tailored to their individual needs.

Applications for Pet Food Science:

* Breed-Specific Diets: Genetic markers guide the development of diets that accommodate variations in metabolism, energy expenditure, and disease susceptibility.
* Disease Prevention: Identification of genes associated with obesity, diabetes, and cardiovascular disorders enables targeted nutritional interventions.
* Nutrigenomics: Investigates how nutrients influence gene expression, leading to personalized diet plans for individual pets.

**2.2 Transcriptomics: Understanding Gene Expression in Response to Diet**

Transcriptomics focuses on the study of gene expression and how it changes in response to various environmental factors, including dietary components. This field is pivotal in understanding how specific nutrients and bioactive compounds influence cellular and metabolic processes at the molecular level. By analyzing RNA transcripts, transcriptomics provides valuable insights into nutrient utilization, metabolic regulation, immune system responses, and other physiological changes that occur after dietary interventions[25]. These insights help in designing functional pet foods that not only meet basic nutritional requirements but also promote optimal health, enhance disease resistance, and address specific health challenges faced by pets. One of the most significant applications of transcriptomics in pet food science is understanding how specific nutrients influence gene expression related to metabolic pathways. For example, omega-3 fatty acids, commonly found in fish oils, are known to have a profound impact on the regulation of inflammation and immune responses. Transcriptomic studies have shown that omega-3 fatty acids can upregulate genes involved in anti-inflammatory pathways, such as those encoding for cytokines and enzymes like cyclooxygenase-2 (COX-2). This modulation of gene expression helps reduce the production of pro-inflammatory molecules and can lower the risk of developing chronic inflammation, a common issue in ageing pets. As a result, diets enriched with omega-3 fatty acids may be particularly beneficial for senior dogs and cats suffering from arthritis or inflammatory diseases, potentially improving their mobility, comfort, and quality of life. In addition to their anti-inflammatory properties, omega-3 fatty acids also influence gene expression in pathways related to lipid metabolism, helping to regulate fat storage and energy production. By modulating the expression of genes involved in the breakdown and utilization of fats, omega-3s can support healthy body weight management and reduce the risk of obesity, which is a growing concern in companion animals [26].

Another important area where transcriptomics has provided valuable insights is in the use of probiotics in pet nutrition. Probiotics are beneficial microorganisms that can be included in pet diets to promote gut health and enhance immune function. Transcriptomic research has shown that probiotics can influence gene expression related to gut barrier integrity, an essential component of digestive health. Specifically, probiotics can upregulate the expression of genes that strengthen tight junctions between intestinal cells, enhancing the gut’s ability to resist harmful pathogens and preventing “leaky gut” conditions that can lead to chronic inflammation and immune dysfunction. In addition to improving gut barrier function, probiotics have been shown to modulate the expression of immune-related genes, supporting a balanced immune response and reducing the risk of gastrointestinal disorders and infections[27]. The impact of probiotics on gene expression extends beyond the gut. Recent studies have suggested that certain strains of probiotics may also affect genes involved in systemic immune regulation, potentially improving an animal’s ability to respond to infections and inflammation throughout the body. This makes probiotics an important component in formulating functional pet foods aimed at strengthening the immune system and improving overall health, especially in pets with compromised immunity or those undergoing medical treatments that may weaken their natural defences. Transcriptomic analyses also provide valuable information on how other nutrients, such as vitamins, minerals, and amino acids, influence gene expression related to specific health conditions. For example, research has shown that certain vitamins like vitamin D play a role in regulating genes involved in bone health and calcium metabolism, while amino acids like arginine and glutamine are involved in cellular repair and immune function [28]. Understanding the gene expression patterns triggered by these nutrients allows pet food formulators to develop diets that not only support basic nutritional needs but also promote health at the molecular level. Overall, transcriptomics is a powerful tool that offers a deeper understanding of how dietary components influence the molecular mechanisms underlying health and disease in pets. By examining the complex interactions between genes and nutrients, researchers can design pet foods that are not only nutritionally complete but also functional in preventing and managing diseases, supporting the ageing process, and promoting overall wellness. As more transcriptomic studies are conducted, the potential for developing targeted, personalized diets tailored to the individual genetic and health profiles of pets continues to grow, paving the way for more precise and effective nutritional interventions[29].

Applications for Pet Food Science:

* Functional Ingredients: Identifies bioactive compounds (e.g., omega-3 fatty acids, probiotics, polyphenols) that regulate gene expression for improved metabolic health.
* Inflammatory Response Regulation: Helps develop diets that reduce inflammation through targeted nutrient-gene interactions.
* Energy Metabolism Optimization: Examines how different macronutrients influence genes related to fat and carbohydrate metabolism.

**Table 2: Key Genes Influenced by Diet in Pets**

| Gene | Function | Dietary Influence |
| --- | --- | --- |
| PPAR-α | Lipid metabolism | Upregulated by omega-3 fatty acids, supporting cardiovascular health |
| SGLT1 | Carbohydrate absorption | Downregulated by low-carb diets, reducing obesity risk |
| IL-10 | Anti-inflammatory response | Upregulated by probiotics, improving gut health |

**2.3 Proteomics: Enhancing Food Quality and Safety**

Proteomics, the large-scale study of proteins and their functions, plays a critical role in advancing pet food science by offering in-depth insights into the protein composition of pet food products. Proteins are essential components of pet diets, providing amino acids for growth, repair, and energy, as well as influencing various physiological processes. By utilizing advanced proteomic techniques, researchers can identify and characterize bioactive peptides, allergens, contaminants, and other functional proteins that contribute to the overall quality and safety of pet food. This field is indispensable not only for assessing the nutritional value of pet food but also for ensuring that formulations are free from harmful substances that could compromise the health and well-being of pets. One of the key applications of proteomics in pet food science is the identification of bioactive peptide short chains of amino acids derived from larger protein molecules. These peptides can have a wide range of therapeutic effects on pet health, including antioxidant, immunomodulatory, antimicrobial, and anti-inflammatory activities [22]. Recent proteomic studies have revealed that hydrolyzed proteins—proteins that have been broken down into smaller peptides through enzymatic processes—contain specific bioactive peptides with significant therapeutic potential. For example, certain peptides derived from hydrolyzed collagen and milk proteins have been shown to possess antioxidant properties that can help mitigate oxidative stress, which is a contributing factor in ageing and various chronic diseases in pets. Additionally, hydrolyzed proteins may contain immunomodulatory peptides that help regulate the immune system, potentially aiding in the management of inflammatory diseases such as arthritis, dermatitis, and inflammatory bowel disease (IBD).These findings are particularly important for developing functional pet foods that not only meet basic nutritional requirements but also support pets suffering from inflammation or immune system imbalances. By incorporating hydrolyzed proteins with specific bioactive peptides, pet food manufacturers can create specialized diets that enhance the body’s ability to manage inflammation, support joint health, and improve overall immune function [23]. This is particularly relevant for senior pets or pets with conditions related to inflammation, as these bioactive peptides may offer natural therapeutic benefits that complement traditional treatments. Proteomics also plays an essential role in ensuring food safety, especially when it comes to identifying and quantifying allergenic proteins in pet food formulations. Many pets, particularly dogs and cats, suffer from food allergies or intolerances that can lead to gastrointestinal disturbances, skin problems, and other adverse health reactions. Proteomic techniques allow researchers to detect specific allergenic proteins, such as chicken, beef, soy, and dairy proteins, that may trigger allergic reactions in sensitive animals. For example, proteomic analysis can be used to accurately identify the presence of chicken or beef proteins in pet foods marketed as hypoallergenic or novel protein diets, ensuring that they do not contain ingredients that could cause harm to pets with known sensitivities[28,29]. This ability to detect even trace amounts of allergens is particularly important for ensuring the safety and efficacy of specialized diets designed for pets with food allergies. Moreover, proteomics enables the detection of contaminants and harmful substances in pet food, such as toxins, pathogens, and residues from chemicals used in food processing. These contaminants, if left undetected, can pose significant health risks to pets. For example, proteomic tools can be used to identify bacterial proteins or endotoxins from pathogens like Salmonella or E. coli, ensuring that pet foods are free from harmful microbial contamination[29,30]. Similarly, proteomics can detect the presence of undesirable substances, such as pesticide residues or heavy metals, that may compromise food safety. This level of analysis is crucial for quality control in pet food production and for meeting regulatory standards set by food safety authorities. The application of proteomics in pet food science is also valuable for monitoring protein quality and ensuring that the protein sources used in pet food are of high nutritional value[18]. By analyzing the protein profiles of different ingredients, researchers can assess their digestibility and biological value, determining how well pets are able to absorb and utilize the proteins in their diets. This helps in optimizing ingredient selection to provide the best quality protein sources for pets, which is particularly important for growth, muscle maintenance, and overall health. Overall, proteomics is an indispensable tool in the development of high-quality, safe, and functional pet foods. It enables the identification of bioactive peptides with therapeutic potential, the detection of allergens and contaminants, and the evaluation of protein quality, all of which contribute to the formulation of safer and more effective diets[20,21]. As proteomic technologies continue to advance, their applications in pet food science will further enhance our ability to create tailored, health-promoting diets that address the unique needs of individual pets, improving their health and quality of life.

Applications for Pet Food Science:

* Bioactive Peptide Identification: Helps develop functional pet foods with immune-boosting and anti-inflammatory properties.
* Food Safety Monitoring: Detects allergenic proteins, pathogens, and contaminants in pet food.
* Quality Control: Ensures consistent nutrient composition in commercial pet food products.

**2.4 Metabolomics: Identifying Biomarkers for Health and Disease**

Metabolomics is a powerful analytical technique that offers a comprehensive understanding of an animal’s metabolic state by measuring the concentrations of metabolites in biological samples such as blood, urine, feces, and saliva. By providing a snapshot of the end products of metabolism, metabolomics enables researchers to gain valuable insights into the biochemical processes occurring within the body[22,31]. This approach is particularly useful in pet food science, as it allows for the detection of early biomarkers of disease, the identification of nutritional deficiencies or imbalances, and the tailoring of dietary interventions to optimize health outcomes. By profiling the metabolites in pets, researchers can monitor their metabolic responses to different diets and environmental factors, ultimately leading to more effective and personalized nutrition strategies. One of the key applications of metabolomics in pet food science is the identification of biomarkers for various diseases, enabling early diagnosis and timely interventions. For example, Trimethylamine N-oxide (TMAO), a metabolite produced from dietary choline and carnitine found in animal products, has been implicated in cardiovascular disease. Elevated levels of TMAO have been associated with an increased risk of atherosclerosis, heart failure, and other cardiovascular conditions in both humans and animals [31,32]. By monitoring TMAO levels in pets, veterinarians and pet food formulators can use it as a biomarker for cardiac health, allowing for early detection of cardiovascular issues and the development of targeted dietary interventions. Diets with reduced levels of red meat, or those enriched with omega-3 fatty acids, may help to modulate TMAO production and reduce the risk of cardiovascular disease in pets, particularly those predisposed to heart conditions [33].Beyond cardiovascular health, metabolomic profiling has also been instrumental in identifying biomarkers for other common diseases in pets, such as kidney disease and diabetes. Chronic kidney disease (CKD) is a prevalent condition in ageing cats and dogs, and early diagnosis is critical for managing the progression of the disease and improving quality of life. Metabolomic studies have revealed specific metabolites that are elevated or depleted in pets with kidney dysfunction, such as asymmetric dimethylarginine (ADMA) and creatinine. By analyzing these metabolites, veterinarians can detect kidney disease in its early stages, even before clinical symptoms become apparent [32,34]. This early detection enables the implementation of dietary interventions, such as protein restriction or the addition of kidney-friendly nutrients like omega-3 fatty acids, antioxidants, and certain vitamins, to help slow the progression of kidney disease and enhance renal function. Similarly, metabolomic profiling has proven valuable in identifying metabolic disruptions associated with diabetes, a growing concern in companion animals, especially in overweight pets. In diabetic animals, changes in glucose and lipid metabolism lead to the accumulation of certain metabolites, such as elevated blood glucose levels, increased ketones, and altered fatty acid profiles. By closely monitoring these metabolites, pet food manufacturers and veterinarians can design more effective dietary interventions for managing diabetes in pets. For example, a diet rich in fibre, low in simple carbohydrates, and formulated to stabilize blood glucose levels can help regulate insulin sensitivity and support metabolic balance in diabetic pets [33,19]. Additionally, metabolomics can be used to assess the efficacy of different therapeutic diets, providing real-time feedback on how well a pet is responding to a given nutritional strategy. Metabolomics also plays a key role in optimizing pet nutrition by identifying metabolic signatures that indicate the body’s response to specific nutrients. By examining the metabolites produced after the ingestion of particular foods or supplements, metabolomic studies can reveal how different ingredients influence metabolic pathways [34]. For instance, a diet rich in certain amino acids, vitamins, or fatty acids may lead to specific changes in metabolic profiles, which can help scientists understand which nutrients are most beneficial for supporting particular physiological functions, such as immune health, gut integrity, and skin condition. Additionally, metabolomic analysis can assist in identifying deficiencies or imbalances in pets’ diets that could lead to health issues[33,36]. For example, low levels of certain micronutrients like magnesium or vitamin B6 might be detected in pets with deficiencies, allowing for the adjustment of the diet to include the necessary supplements or ingredient changes. This approach not only improves the overall health of the pet but also ensures that the diet provides the right balance of nutrients for optimal metabolic function. As metabolomics continues to evolve, its applications in pet food science will become increasingly precise and tailored to the individual needs of pets. The ability to track changes in metabolites in real time offers valuable insights into formulating personalized diets that address specific health conditions or metabolic needs. Ultimately, metabolomics empowers researchers and pet food manufacturers to move beyond one-size-fits-all dietary recommendations and create precision diets that support better health outcomes and disease prevention for pets, especially those with genetic predispositions, chronic conditions, or specific metabolic needs.

**Table 3: Key Metabolites Associated with Pet Health**

| Metabolite | Role | Health Implications |
| --- | --- | --- |
| TMAO | Gut microbiome metabolite | Linked to cardiovascular health |
| Creatinine | Kidney function marker | Indicator of renal health |
| Glucose | Energy metabolism | Marker for diabetes risk |

**2.5 Microbiomics: Optimizing Gut Health and Immunity**

Microbiomics is the study of the gut microbiome, the vast community of microorganisms, including bacteria, fungi, viruses, and other microbes, that reside in the gastrointestinal (GI) tract. These microbes play a crucial role in numerous aspects of pet health, particularly in digestion, immunity, and behaviour [31]. Advances in microbiomics have highlighted the importance of a balanced and diverse gut microbiota in maintaining overall health and preventing disease. The gut microbiome is involved in the breakdown and fermentation of dietary fibres, the synthesis of essential vitamins, and the modulation of the immune system. Additionally, emerging evidence suggests that the microbiome can even influence behaviours, such as stress response and mood regulation, through the gut-brain axis[32,33]. Diet is one of the most significant factors influencing the composition and diversity of the gut microbiome. What pets eat directly affects the types of microbes that flourish in the gut, which in turn impacts nutrient absorption, metabolic health, and immune function. Diets high in fibre, for example, have been shown to promote the growth of beneficial bacteria, such as Bifidobacterium and Lactobacillus, which are known for their positive effects on gut health. These bacteria help digest complex carbohydrates that the pet’s digestive enzymes cannot break down on their own. Through the fermentation of dietary fibres, these beneficial bacteria produce short-chain fatty acids (SCFAs), such as butyrate, which serve as an energy source for colon cells and have anti-inflammatory properties. SCFAs are also vital for maintaining gut barrier integrity, preventing leaky gut syndrome, and supporting the overall health of the gastrointestinal tract [35,36]. In addition to promoting beneficial bacteria, high-fibre diets can help regulate bowel movements and prevent gastrointestinal (GI) issues, such as constipation, diarrhoea, and colitis. By increasing the diversity of the gut microbiome, high-fibre diets help maintain a balanced microbial ecosystem, reducing the risk of dysbiosis (microbial imbalance) that can lead to gut-related diseases and conditions. Furthermore, the inclusion of prebiotics and probiotics in pet diets is a growing area of interest in microbiomics research. Prebiotics are non-digestible food ingredients that stimulate the growth or activity of beneficial microbes in the gut [36]. Common prebiotics, such as oligosaccharides found in certain fibres, promote the growth of specific beneficial bacteria, including Bifidobacterium and Lactobacillus, which are associated with improved gut health and immune function. Prebiotics support the microbiome by providing the necessary substrates for these beneficial microbes to thrive, enhancing the microbial diversity and overall health of the GI tract [36,37]. Probiotics, on the other hand, are live beneficial microorganisms that, when administered in adequate amounts, confer health benefits to the host. Probiotics have been shown to enhance gut microbiome diversity, improve digestion, and modulate immune responses. For example, the introduction of probiotic strains such as Lactobacillus or Enterococcus has been shown to promote the production of beneficial metabolites and modulate the immune system to reduce inflammation, protect against pathogens, and strengthen the gut’s mucosal barrier[38]. Probiotics are particularly beneficial in maintaining a balanced microbiome in pets that are prone to gastrointestinal diseases, such as inflammatory bowel disease (IBD), irritable bowel syndrome (IBS), or food intolerances.

One of the key roles of the gut microbiome in pet health is its influence on immune function. A significant portion of the immune system resides in the GI tract, where it interacts with the gut microbiota to regulate both local and systemic immune responses. A healthy, diverse microbiome can enhance the immune system’s ability to recognize and respond to pathogens while maintaining tolerance to harmless substances, such as food particles and beneficial bacteria. Dysbiosis, on the other hand, has been linked to a weakened immune system, making pets more susceptible to infections, allergies, and autoimmune diseases.[11,38] By supporting a healthy gut microbiome with prebiotics, probiotics, and fibre, pet food formulations can help strengthen the immune system, reduce inflammation, and protect against a range of diseases. In addition to immune health, gut microbiomes have been found to influence metabolic health, including energy metabolism and weight regulation. Imbalances in gut microbiota composition have been associated with conditions such as obesity, metabolic syndrome, and insulin resistance. Certain bacterial species are involved in the fermentation of dietary fibres into SCFAs, which are not only beneficial for gut health but also play a role in regulating appetite and fat storage [32,39]. For instance, butyrate has been shown to enhance insulin sensitivity and promote fat oxidation, potentially aiding in weight management. On the other hand, an overgrowth of harmful bacteria may lead to excessive nutrient absorption and fat accumulation, contributing to obesity. By incorporating microbiome-supporting ingredients into pet foods, such as fibre, prebiotics, and probiotics, manufacturers can help mitigate the risk of metabolic disorders and promote healthy weight management. Recent studies have also shown that gut microbiomes may play a role in influencing pet behaviour, particularly in terms of anxiety, stress, and mood regulation [33,40]. The gut-brain axis, a bidirectional communication pathway between the gut and the brain, has been shown to mediate the effects of the microbiome on behaviour. For example, pets with an imbalanced gut microbiome may experience heightened stress responses or anxiety. Probiotics, prebiotics, and other diet-related interventions that promote a healthy microbiome may help improve mood and reduce anxiety, particularly in pets with a history of behavioural issues or stress-related conditions. Microbiomics has become a crucial area of research in pet food science, as it provides new insights into how the gut microbiome influences digestion, immunity, metabolic health, and even behaviour [18,19]. By shaping the gut microbiota through targeted dietary interventions, such as high-fibre diets, prebiotics, and probiotics, pet food formulators can create products that enhance gut health, reduce the risk of gastrointestinal diseases, support immune function, and promote overall well-being. As our understanding of microbiomes continues to evolve, the potential for developing more personalized and effective nutrition strategies for pets grows, offering the possibility of improving the health and quality of life of pets through microbiome-targeted diets.

Applications for Pet Food Science:

* Microbiome-Targeted Diets: Designing pet foods that support a balanced gut microbiota.
* Probiotic and Prebiotic Formulations: Enhancing digestive health and immune function.
* Disease Management: Addressing IBD and dysbiosis through diet.

**3. Conclusion**

The integration of omics technologies—genomics, transcriptomics, proteomics, metabolomics, and microbiomics—has revolutionized pet food science, providing an in-depth understanding of the biological mechanisms that influence nutrient metabolism, gut health, immune function, and disease susceptibility. Unlike traditional pet food formulations, which focus primarily on meeting basic nutritional requirements, omics-based approaches enable the development of precision nutrition strategies tailored to individual pets. Genomics has provided insights into breed-specific dietary needs, enabling the formulation of customized diets that address genetic predispositions to conditions such as obesity, diabetes, and cardiovascular disease. Transcriptomics has revealed how dietary components modulate gene expression, allowing researchers to incorporate functional ingredients that regulate inflammation, metabolism, and immune responses. Proteomics has enhanced food safety and quality control, enabling the detection of allergens, bioactive peptides, and contaminants in pet food products. Metabolomics has helped identify biomarkers for metabolic disorders, facilitating early disease detection and personalized dietary interventions. Lastly, microbiomics has deepened our understanding of the gut microbiome's role in digestion, immunity, and behaviour, supporting the use of probiotics and prebiotics in pet food formulations. Despite these advancements, several challenges remain in translating omics research into commercial pet food applications. The high cost of omics technologies, the complexity of multi-omics data integration, and the limited availability of species-specific databases are significant barriers that need to be addressed. Moreover, longitudinal studies are required to assess the long-term effects of omics-based dietary interventions on pet health. In summary, omics technologies are reshaping pet food science, allowing for a shift from generalized dietary recommendations to personalized pet nutrition. As research progresses, these technologies will play a pivotal role in improving pet health, longevity, and overall well-being through scientifically validated, data-driven dietary solutions.

* 1. **Future Directions in Omics-Based Pet Food Research**

1 Integration of Multi-Omics Approaches

* Future research should focus on integrating data from multiple omics fields (genomics, transcriptomics, proteomics, metabolomics, and microbiomics) to develop a holistic understanding of pet nutrition. By using artificial intelligence (AI) and machine learning algorithms, researchers can analyze complex multi-omics datasets, identifying key interactions between dietary components, gene expression, protein synthesis, metabolic pathways, and gut microbiome composition.

2 Expansion of Species-Specific Omics Databases

* Most omics studies have been conducted on dogs and cats, leaving other companion animals underrepresented in scientific literature. Future research should expand species-specific databases to include rabbits, birds, reptiles, and exotic pets, ensuring that precision nutrition strategies are applicable across a broader range of species.

3 Longitudinal Studies on Omics-Driven Diets

* While short-term studies have demonstrated the benefits of omics-based diets, long-term clinical trials are necessary to assess the sustained impact of precision nutrition on pet health, longevity, and disease prevention. These studies should evaluate how omics-driven diets influence metabolic adaptations, gut microbiome stability, and ageing-related conditions over time.

4 AI-Powered Personalized Pet Nutrition

* Artificial intelligence (AI) and big data analytics will play a crucial role in processing omics data to develop real-time, personalized nutrition recommendations for pets. Future pet food products may incorporate AI-driven formulation tools that analyze an individual pet’s genetic, metabolic, and microbiome profile to recommend optimal dietary solutions.

5 Sustainable and Alternative Pet Food Ingredients

* As pet food production shifts towards greater sustainability, omics technologies can be used to identify novel, nutrient-rich, and environmentally friendly ingredients, such as alternative protein sources (insect-based proteins, lab-grown meat, algae), plant-based formulations, and fermented foods. Research should focus on how these alternative ingredients influence pet metabolism, microbiome diversity, and overall health.

6 Regulatory and Ethical Considerations

* As omics-based pet nutrition becomes more prevalent, regulatory frameworks must evolve to ensure that precision pet food formulations are safe, scientifically validated, and ethically produced. Future studies should explore the ethical considerations of genetic testing in pets, the safety of gene-edited pet foods, and the regulatory policies governing precision nutrition technologies.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Option 2:

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology

Details of the AI usage are given below:

1.

2.

3.

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