Nutrigenomics in Aquaculture: Decoding Gene–Diet Interactions for Sustainable Fish Production

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Abstract

Aquaculture stands as a vital and fast-growing sector, delivering nutrient-rich food and fulfilling protein needs with minimal carbon emissions. Advances in production technologies, health strategies, and insights into the genetics of aquatic species have fueled this progress. Sustainable aquaculture growth hinges on a deep grasp of growth mechanisms and their molecular foundations. Genomic and molecular studies illuminate feed metabolism and utilization in fish, while enabling nutritional tweaks to gene expression for superior feed efficiency and performance. Nutrigenomics bridges nutrition and genomics, showing how diet influences gene activity. In aquaculture, it supports creation of high-performance feeds that boost economics, functionality, and fish welfare.

Keywords: Nutrigenomics, Aquaculture sustainability, Fish genomics, Feed efficiency, Gene expression

Introduction

Nutrigenomics merges bioinformatics, nutrition, genomics, molecular biology, and epidemiology to explore how nutrients interact with cellular processes and modify genetic expression (Neeha et al. 2013). It reveals nutrient effects on gene regulation through tools like transcriptomics, proteomics, genomics, and metabolomics, aiding insights into diet-driven changes in gene activity, metabolic pathways, and homeostasis (Jeevagan et al. 2017; Lende et al. 2014; Mullar et al. 2003). By analyzing genetic profiles alongside diet-chronic disease links, it forecasts species-specific nutritional requirements while pinpointing genes tied to diet-induced responses, polymorphisms, and environmental influences (Lende et al. 2014; Mullar et al. 2003). This field reveals species-specific nutrient responses for instance, why carnivorous fish poorly utilize carbohydrates compared to herbivorous ones while mapping polymorphisms and environmental influences on physiology (Lende et al. 2014; Mullar et al. 2003). By analyzing genetic profiles alongside diet-disease links, nutrigenomics forecasts tailored nutritional needs, replacing trial-and-error feeds with genomics-guided diets that enhance feed efficiency, reduce waste, and boost resistance to stressors in species like salmon and tilapia. Key aquaculture benefits include developing sustainable alternatives to fishmeal/oil by identifying lipid metabolism genes, improving FCR through enzyme upregulation (e.g., carbohydrate digestion in plant-based feeds), and creating functional feeds that upregulate immunity genes against pathogens. Ultimately, it drives economic gains via "designer feeds" that minimize pollution, accelerate growth compensation during fasting cycles, and elevate animal welfare in intensive systems.

Origin of Nutrigenomics

Investigating human disease origins often sparks the nature-nurture debate, with biologists today recognizing that neither genetics nor environment alone fully explains the molecular mechanisms controlling health. Typically, a single gene or mutation merely signals susceptibility to certain conditions (Mead, 2007). The 1990s Human Genome Project, which sequenced the entire human genome, provided nutrigenomics' initial breakthrough. By 2007, studies had uncovered numerous gene-diet-disease connections (Neesha et al., 2012). Initially focused on how nutrients modify inherited traits and gene expression, the field now encompasses diet's protective role against genomic damage (Mead, 2007). It also covers gene-diet interactions termed inborn errors of metabolism (Neesha et al., 2012). In fish, delivering balanced diets meeting all nutrient needs during key developmental stages is essential to prevent growth stunting and infections, ensuring optimal welfare and performance (Oliva-Teles, 2012).

Nutrigenomics in Action

Most aquaculture nutrigenomics research relies on transcriptomics, analyzing mRNA transcription outputs to understand nutrient effects on genes. These studies use reverse transcription polymerase chain reaction (RT-PCR): total mRNA converts to cDNA, enabling various PCR methods. Semi-quantitative and real-time PCR are primary techniques to detect transcriptome abundance differences across dietary treatments. DNA microarray technology offers a comprehensive view of an organism's full genomic response to nutrients or diets, beyond single genes. Yet, its use in fish nutrition remains constrained by the need for species-specific genetic markers. The candidate gene approach selects potential risk genes based on known biological roles; though limited in application, it employs in vitro cell cultures to test positive or negative links between gene activity, nutrition, and metabolism. (Iqbal et al., 2025).

Applications of Nutrigenomics

Nutrigenomics provides critical insights into nutrient absorption across fish organs and tissues. For example, liver-specific glucokinase a unique hexokinase remains unaffected by glucose-6-phosphate inhibition that suppresses other hexokinases elsewhere, while insulin simultaneously curbs muscle lipoprotein lipase (LPL) and fat deposition yet boosts adipose LPL and lipogenesis (Rocha et al., 2015). It evaluates species-specific nutrient responses, revealing why high-carbohydrate diets suppress gluconeogenesis in humans but not fish, thus explaining variable sensitivities (Hakim et al., 2018). Nutrigenomics also maps physiological metabolic shifts, such as salmon red muscle's 60% β-oxidation in smolt stage versus 10% in adults. Diet formulation benefits immensely: herbivorous fish upregulate carbohydrate-digesting enzymes upon intake, unlike carnivores, allowing tailored feeds that maximize ingredient utilization (Hakim et al., 2018). It elucidates dietary control of metabolism exemplified by DHA's retro-inhibition of delta-6 desaturase and clarifies cellular responses, like carnivorous fish's poor carbohydrate handling due to dysregulated insulin (Hakim et al., 2018). Husbandry improves through integration with hormones like ghrelin and leptin, modulated by environment to optimize feed intake (Volkoff et al., 2005). It identifies metabolic drivers, such as elevated muscle adipose LPL expression catabolizing fats for growth energy, often raising feed protein/lipid at carbohydrate's expense peaking in summer with higher carcass fat (Mead et al., 2002). Nutrigenomics further dissects metabolism influencers, distinguishing fish hexokinases from LPL genes, and probes nutrient transport: glucokinase ignores dietary glucose unlike others (Wilson, 1994), while Na-PO4 co-transporters adapt to phosphate levels (Reed, 2014). This enables testing preferred nutrient forms for enhanced uptake, revolutionizing precision aquafeeds.

Optimizing Aquafeed: Protein-Lipid Balance via Nutrigenomics

Diet plays a pivotal role in the growth and development of aquatic species (Vasilyeva et al., 2016). Delivering balanced feeds that fulfil precise nutritional requirements during key developmental stages is essential for maintaining fish health, performance, and resistance to infections or stunted growth. Protein represents the most expensive yet critical component of aquafeed, with rainbow trout requiring approximately 40% and fry up to 45% (Jobling, 2012). However, high protein levels inflate costs and elevate nitrogen pollution in culture systems (Li et al., 2012). Lipids serve as the primary energy source and deliver essential fatty acids for growth (Watanabe, 1982). Research shows that reducing protein while increasing lipids enhances protein synthesis efficiency and minimizes nitrogen waste (Chen et al., 2017; Li et al., 2012; Morais et al., 2005; Valente et al., 2011). Fish oil proves invaluable in carnivorous marine species diets due to its rich n-3 polyunsaturated fatty acids (n-3 PUFA), which bolster immunity and development rates (Gu et al., 2019; Ruyter et al., 2015). Optimizing lipid levels prevents excessive visceral/muscle fat accumulation—which compromises flesh quality and consumer safety—while averting fatty deposits and growth delays (Chatzifotis et al., 2010; Rahim et al., 2015). Thus, nutrigenomics-guided lipid balancing sustains market value, health, and productivity.

Nutrigenomics: Precision Feeds for Superior Fish Immunity

Nutrigenomics enhances fish immune function by elucidating how dietary components regulate gene expression in innate and adaptive pathways, enabling functional feeds that suppress inflammation, boost antiviral responses, and fortify pathogen resistance. Omics technologies like RNA-seq and microarrays reveal how n-3 PUFAs from fish/krill oil dampen excessive cytokines during piscine reovirus or CMS infections in salmon, reducing viral loads and heart pathology while upregulating interferon/NK cell genes for clearance (Martin et al., 2017). Essential amino acids modulate TOR/NF-κB/Nrf2 signaling to elevate antioxidant enzymes, downregulate pro-inflammatory cytokines (e.g., IL-1β, TNF-α), and amplify anti-inflammatory IL-10, strengthening phagocyte/complement activity and mucosal barriers (GALT/SALT/GIALT). Selenium (Sel-Plex®) outperforms inorganic forms by hyperstimulating head kidney interferon-γ and cell-mediated immunity transcripts, while plant additives/glucosinolates trigger MHC I/II and heme-denial responses against sea lice (Pacitti et al., 2016). Fasting studies confirm downregulated immunity genes recover via targeted refeeding, preventing bacterial (55% dominant) outbreaks; microbiome shifts from omega-3s favor beneficial Lactobacillus/Akkermansia, curbing inflammation. Overall, nutrigenomics designs precision diets reducing mortality, accelerating recovery, and sustaining welfare in intensive aquaculture (Skugor et al., 2016).

Conclusion

Nutrigenomics studies how nutrients and dietary components interact with genes to influence health, metabolism, and gene expression. It explores the effects of food on the genome, proteome, and metabolome at a molecular level. Nutrigenomics revolutionizes aquaculture by decoding diet-gene interactions, enabling precision feeds that optimize growth, immunity, and reproduction while slashing costs and pollution. From tailoring protein-lipid balances for trout to functional feeds combating bacterial outbreaks in salmon, it delivers sustainable gains in FCR, welfare, and resilience against stressors. As omics tools advance alongside CRISPR editing, nutrigenomics promises "designer" nutrition herbivore enzymes in carnivores, pathogen-proof microbiomes aquaculture into an era of molecular efficiency and global food security. With better tools and gene editing, it makes "custom" nutrition like plant-digesting enzymes for meat-eaters or disease-resistant gut bacteria leading to efficient, sustainable fish production for global food needs.

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