Implantable Biosensors For In Vivo Nutrient Utilization Tracking

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Abstract

Efficient nutrient utilization is essential for sustainable aquaculture, as feed represents the major production cost and poor metabolic efficiency leads to environmental nutrient discharge. Conventional evaluation methods, including growth performance and feed conversion ratio, provide limited and low-frequency data, failing to capture rapid metabolic changes in individual fish. Implantable biosensors offer a promising solution by enabling continuous, in vivo monitoring of key metabolites such as glucose, an important indicator of energy balance and stress. This article outlines the principles of electrochemical and optical implantable biosensors and their application in real-time glucose monitoring in fish. These systems link feeding regimes and environmental conditions with physiological responses, supporting precision feeding and welfare assessment. Although challenges such as long-term stability and biocompatibility remain, advances in sensor technology and data analytics highlight the strong potential of implantable biosensors to enhance efficiency, sustainability, and productivity in modern aquaculture.

Keywords: Implantable biosensors, Nutrient utilization, Glucose monitoring, Precision aquaculture and Fish stress physiology

Introduction

Efficient nutrient utilization is central to modern aquaculture because feed costs account for a major proportion of production expenses and poor feed conversion can lead to environmental pollution through excess nitrogen and phosphorus release (Rodrigues et al., 2020). Traditional approaches to assessing nutrient utilization rely on periodic sampling of blood or tissues, growth measurements, and feed conversion ratios, which yield low-frequency, population-level information rather than continuous, individual-level profiles (Rodrigues et al., 2020). Implantable biosensors, by contrast, offer continuous monitoring of key metabolites such as glucose that reflect energy balance, stress, and nutritional status in individual fish (Endo et al., 2009; Wu et al., 2015). By embedding sensing elements inside the body and transmitting data wirelessly or reading it optically, these systems can capture dynamic responses to diet composition, feeding schedules, and environmental changes that would otherwise be missed (Endo et al., 2009; Wu et al., 2020). The objective of this article is to review implantable biosensor technologies for in vivo nutrient utilization tracking in fish, with emphasis on sensor principles, implantation strategies, representative case studies, and future prospects.

Concept of Nutrient Utilization Tracking in Fish

Nutrient utilization in fish involves ingestion, digestion, absorption, metabolic transformation, and excretion of dietary components, ultimately determining growth performance and health status (Rodrigues et al., 2020). Biochemical indicators that reflect nutrient utilization include blood glucose as an energy status marker, lactate as a proxy for anaerobic metabolism, free amino acids and lipids as substrate pools, and nitrogenous waste products such as ammonia and urea as end points of protein catabolism (Rodrigues et al., 2020). In practice, most existing implantable systems in fish target glucose as a proxy for nutritional and stress status because glucose is relatively straightforward to detect electrochemically and shows measurable fluctuations in response to feeding and environmental or handling stress (Endo et al., 2009; Wu et al., 2015). For example, sustained elevations in blood glucose can indicate respiratory or nutritional disturbances, whereas postprandial glucose curves mirror carbohydrate utilization and endocrine control processes (Endo et al., 2009). Continuous monitoring of glucose in vivo therefore provides a practical starting point for approximating nutrient utilization patterns under different feeding regimes and environmental conditions in aquaculture systems (Wu et al., 2015; Wu et al., 2020).

Principles of Implantable Biosensors

Implantable biosensors typically integrate a biorecognition element with a physicochemical transducer in a miniaturized device that can operate within body fluids or tissues (Zhou et al., 2023). Common biorecognition elements include enzymes such as glucose oxidase, nucleic-acid-based aptamers, and fluorescent nanosensor chemistries that are tailored to specific target analytes (Zhou et al., 2023; Lee et al., 2019). In glucose biosensors used for fish, glucose oxidase catalyses the oxidation of glucose to gluconolactone with concurrent production of hydrogen peroxide, and the hydrogen peroxide is then oxidized at an electrode surface to generate a current proportional to glucose concentration (Endo et al., 2009; Wu et al., 2015). These electrodes are commonly fabricated from platinum–iridium or related metals and are coated with permselective films such as Nafion to suppress interference from anionic species like ascorbate or urate that can otherwise affect the electrochemical signal (Endo et al., 2009). Alternative transduction platforms include hydrogel-based optical nanosensors, where changes in fluorescence intensity or wavelength encode analyte concentration and can be read non-invasively through tissue by an external optical device (Lee et al., 2019).

Implantation Sites and System Architecture

Choice of implantation site strongly influences the sensor's analytical performance, response time, and animal welfare impact (Endo et al., 2009; Wu et al., 2015). One widely used site is the eyeball interstitial sclera fluid (EISF), where a needle-type glucose sensor is inserted into scleral fluid; glucose levels in EISF have been shown to correlate closely with blood glucose in fish (Endo et al., 2009; Wu et al., 2015). Abdominal cavity implantation has also been investigated, positioning enzyme or microsensor probes in the peritoneal cavity so that they interact with circulating interstitial fluids within the body (Wu et al., 2017; Wu et al., 2020). In implanted optical nanosensor systems, hydrogel particles containing fluorescent probes are injected intramuscularly and remain localized, allowing excitation and detection through overlying tissues using a wearable optical reader (Lee et al., 2019). To achieve continuous monitoring, such implants are coupled to external modules either a wireless transmitter package attached to the fish or a wearable optical interface that provide power, perform initial signal processing, and transmit or display data to a base station or observer (Endo et al., 2009; Wu et al., 2020; Lee et al., 2019).

Representative Studies in Fish

Wireless Enzyme Sensor for Glucose

One of the earliest and most influential demonstrations of implantable biosensors in fish was the wireless enzyme sensor system for real-time glucose monitoring developed by Endo and colleagues (Endo et al., 2009). Their system employed a needle-type platinum–iridium electrode coated with Nafion and immobilized glucose oxidase, which was implanted into the EISF of individual fish and connected to a miniaturized transmitter module externally attached to the fish's body (Endo et al., 2009). In vitro characterization showed a linear response range from 0.18 to 144 mg/dL with a detection limit of 0.18 mg/dL, indicating suitability for physiologically relevant glucose concentrations in fish (Endo et al., 2009). In vivo experiments in freely swimming fish over three days demonstrated strong agreement between sensor-derived EISF glucose values and concurrently measured blood glucose, validating the correlation between the two compartments (Endo et al., 2009). The authors concluded that continuous glucose monitoring using such implants can reveal both stress-induced and nutritionally induced changes in metabolic status, laying a foundation for in vivo nutrient utilization tracking (Endo et al., 2009).

Real-Time Stress and Nutrient-Related Monitoring

Building on this concept, Wu and co-workers developed integrated biosensor systems for real-time fish stress monitoring that used glucose as a combined stress and metabolic indicator (Wu et al., 2015; Wu et al., 2020). In one study, their integrated biosensor platform measured glucose electrochemically and drove a multifunctional LED display that visualized stress levels in different colors—green, yellow, or red based on glucose-derived signals processed by the system (Wu et al., 2020). Experiments with Nile tilapia exposed to different dissolved ammonia concentrations in water (for example, 10–20 mg/L) showed that the implanted sensor system detected corresponding increases in glucose, linking environmental nutrient pollution, physiological stress, and metabolic response in real time (Wu et al., 2020). Subsequent work expanded applicability by relocating sensors into the abdominal cavity and assessing sensor responses to glucose in abdominal interstitial fluid, which is more directly connected to systemic metabolism than some peripheral sites (Wu et al., 2017). These studies highlight how implantable glucose biosensors can simultaneously inform on stress physiology and nutrient-related metabolic changes in aquaculture settings (Wu et al., 2015; Wu et al., 2020).

Implanted Nanosensors in Marine Organisms

Lee and collaborators introduced implanted fluorescent nanosensors in marine organisms as a new strategy for physiological biologging in aquatic animals (Lee et al., 2019). Their system employed hydrogel-based nanosensors injected into muscle tissue to detect analytes such as riboflavin, with a wearable optical device used to excite the sensors and read fluorescence signals through the skin and surrounding tissues (Lee et al., 2019). Tests in multiple aquatic vertebrates showed that the nanosensor implants were mechanically stable and biocompatible over extended periods and that robust sensor signals could be acquired from freely moving animals without restraining those (Lee et al., 2019). Although these initial implementations focused on riboflavin as a model analyte for proof-of-concept, the same platform could be adapted to nutrient-related metabolites by changing the fluorophore or recognition chemistry, providing a non-electrochemical route to in vivo nutrient utilization tracking (Lee et al., 2019). This work demonstrates that soft, optical implants can complement electrochemical enzyme sensors in future aquaculture monitoring systems.

Relevance to Nutrient Utilization in Aquaculture

Implantable biosensors make it possible to obtain high-resolution time series of metabolite levels, revealing rapid metabolic responses to feeding, fasting, and environmental fluctuations that are not captured by conventional periodic sampling (Endo et al., 2009; Wu et al., 2015). For example, continuous glucose monitoring can reveal post-feeding peaks, recovery times, and stress-related hyperglycemic episodes, which together provide insights into carbohydrate utilization, endocrine control, and the effects of dietary formulations (Endo et al., 2009; Wu et al., 2020). When combined with data on feed intake, growth rate, and body composition, such metabolite time series can be used to estimate how different diets, feeding strategies, or environmental conditions influence internal nutrient partitioning and energy allocation (Rodrigues et al., 2020; Wu et al., 2015). Continuous monitoring also supports welfare assessment because persistent deviations from normal metabolite patterns may signal chronic stress, underfeeding, or subclinical disease, enabling early detection and intervention in aquaculture facilities (Wu et al., 2015; Wu et al., 2020). In large-scale production, these biosensor systems could be integrated into precision feeding platforms that automatically adjust ration size or composition based on real-time physiological feedback from representative fish (Rodrigues et al., 2020).

Technical Challenges

Despite significant progress, several key challenges currently limit large-scale deployment of implantable biosensors for nutrient utilization tracking in fish (Zhou et al., 2023; Lee et al., 2019). Long-term stability remains a major issue because enzyme activity can degrade over time, biofouling layers can form on sensor surfaces, and foreign body responses can encapsulate implants, all of which reduce sensitivity and accuracy during extended use (Gough et al., 2007; Zhou et al., 2023). Biocompatibility and welfare considerations require that implantation procedures cause minimal tissue damage and that devices do not impair essential functions such as vision, swimming performance, or predator avoidance (Endo et al., 2009; Lee et al., 2019). Power supply and wireless communication modules must be compact, hydrodynamically acceptable, and robust to the aquatic environment, which is particularly challenging in small fish and marine species that experience variable pressures and salinities (Endo et al., 2009; Wu et al., 2020). Furthermore, most current systems monitor only one or a few metabolites typically glucose whereas comprehensive nutrient utilization tracking would benefit from multiplexed sensing of glucose, lactate, amino acids, and nitrogenous waste products within the same individual (Zhou et al., 2023; Rodrigues et al., 2020).

Future Directions

Advances in materials science and microfabrication are likely to drive the next generation of implantable biosensors for nutrient utilization monitoring in fish (Zhou et al., 2023). Flexible and stretchable substrates, including soft polymers and hydrogels, can reduce mechanical mismatch between sensor implants and surrounding tissues, which may improve comfort, reduce inflammatory responses, and enhance signal stability over time (Zhou et al., 2023; Lee et al., 2019). Nanostructured electrodes and improved enzyme immobilization chemistries may help prolong catalytic activity while mitigating biofouling, thereby extending the operational lifetime of electrochemical sensors in vivo (Gough et al., 2007; Zhou et al., 2023). Optical nanosensors can be tuned to new analytes, including nutrient-related metabolites, by altering the fluorophore or receptor chemistry, enabling multiplexed detection with relatively simple external optics and minimal electronic complexity on the implant (Lee et al., 2019). In parallel, integration of sensor outputs with data analytics and machine learning could allow complex metabolite time series to be translated into actionable indices of feed efficiency, health status, and environmental suitability, supporting real-time management decisions in intensive aquaculture systems (Rodrigues et al., 2020).

Conclusion

Implantable biosensors constitute a promising frontier for in vivo nutrient utilization tracking in fish because they provide continuous, individual-level insights into metabolic responses to diet and environment (Endo et al., 2009; Wu et al., 2015; Lee et al., 2019). Pioneering work on wireless glucose enzyme sensors and implanted optical nanosensors has demonstrated the technical feasibility of long-term monitoring and highlighted the value of metabolite tracking for assessing both stress physiology and nutritional status in aquatic animals (Endo et al., 2009; Wu et al., 2020; Lee et al., 2019). At the same time, important challenges remain in improving long-term stability, ensuring biocompatibility, miniaturizing power and communication modules, enabling multiplexed sensing, and developing cost-effective deployment strategies suitable for commercial farms (Zhou et al., 2023; Gough et al., 2007). Continued interdisciplinary research at the interface of sensor engineering, fish physiology, aquaculture management, and data science will be essential to realize the full potential of implantable biosensors in precision feeding and sustainable fish production (Rodrigues et al., 2020; Wu et al., 2015).

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