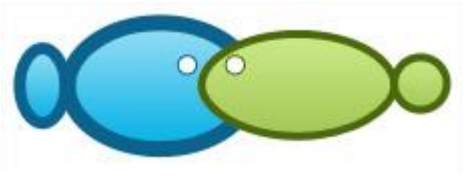

Review of dietary strategies for glass eels (*Anguilla* sp.): impact of plant-based protein diets on growth, immunity, and intestinal development

[1]Endhay K. M. Kontara, [2]Lusi H. Suryaningrum, [1]Adang Saputra, [1]Siti Murniasih, [1]Lies Emmawati, [1]Taukhid Taukhid, [1]Edy B. Kholidin, [1]Yohanna R. Widyastuti, [1]Abidin Nur II

[1] Research Center for Fisheries, National Research and Innovation Agency of Indonesia (BRIN), Cibinong, West Java, Indonesia; [2] Research Center for Applied Zoology, National Research and Innovation Agency of Indonesia (BRIN), Cibinong, West Java, Indonesia. Corresponding author: L. H. Suryaningrum, lusi006@brin.go.id

Abstract. Eel aquaculture, particularly the adaptation of glass eels (*Anguilla* sp.) to suitable diets, is crucial for sustainable industry growth. Traditional reliance on fishmeal-based diets has posed significant sustainability challenges, driving the exploration of plant-based alternatives. This review critically evaluates the impacts of plant-based protein diets on the growth, survival, and intestinal development of glass eels, emphasizing the necessity of precise formulation to ensure nutritional adequacy. The transition from fishmeal to plant-based proteins offers a promising pathway to reduce environmental impacts and enhance sustainability in eel farming. However, challenges remain, particularly regarding the digestibility and nutritional profile of plant-based diets compared to fishmeal. Key findings indicate that while plant-based diets can support growth and survival, they require careful formulation and supplementation to prevent adverse effects on intestinal maturation and overall health. The review also explores the potential of functional additives, such as probiotics and prebiotics, to enhance gut health and nutrient absorption in plant-based diets. Additionally, the long-term effects of early dietary interventions on the digestive efficiency and health of glass eels are discussed, highlighting the importance of early nutritional programming. The transition to plant-based diets in eel aquaculture, while promising, must be managed with a multidisciplinary approach, considering the complex interplay between diet, intestinal development, and long-term health outcomes. This review underscores the need for continued research into optimizing plant-based diets to ensure the sustainability and viability of glass eel populations in aquaculture, contributing to the broader goal of reducing the industry's reliance on wild-caught juveniles and promoting sustainable aquaculture practices.
Key Words: *Anguilla* sp., fishmeal alternatives, intestinal development, plant-based protein, sustainable aquaculture.

Introduction. Eel aquaculture, a practice deeply intertwined with the harvesting and cultivation of wild-caught juveniles such as glass eels (*Anguilla* sp.), is a highly valuable yet complex industry that faces significant challenges. One of the primary issues is the heavy reliance on wild-caught juveniles, as large-scale artificial breeding of eels remains elusive. The current industry practices necessitate the capture of wild glass eels, which are then raised in aquaculture settings until they reach a commercially viable size. This dependence on wild-caught eels not only places pressure on natural eel populations but also exposes the industry to uncertainties in the supply chain and fluctuating market prices (Jang et al 2022; Pons-Hernández 2024).

Eel aquaculture is particularly vulnerable due to the biological complexity of the eel life cycle, which includes multiple developmental stages from leptocephalus larvae to glass eels, and eventually to elvers and adult eels. The transition from glass eel to elver is a critical phase that requires precise management in aquaculture settings. During this stage, eels undergo significant physiological changes, including the development of their digestive systems and the adaptation to different environmental conditions (Taqwa et al 2018). This transition is further complicated by the challenges of maintaining optimal

rearing conditions, which are essential for ensuring high survival rates and healthy growth.

A major concern in eel aquaculture is the environmental impact of farming practices. The use of plastic products such as nylon cages and polyethylene films in eel farming has been associated with microplastic contamination in aquaculture ponds (Lv et al 2020). This contamination poses risks not only to the health of the eels but also to the broader aquatic ecosystem. As the demand for sustainable aquaculture practices grows, there is increasing pressure on the industry to adopt methods that minimize environmental harm while maintaining productivity.

Another critical issue facing eel aquaculture is the lack of successful large-scale artificial breeding techniques. Despite ongoing research efforts, the industry still relies heavily on wild-caught glass eels, which are becoming increasingly scarce due to overfishing and habitat loss (Nakase et al 2014). The failure to develop effective captive breeding programs has led to a decline in wild eel populations, prompting concerns about the long-term sustainability of the industry (Arai 2014). This situation underscores the urgent need for innovations in breeding and rearing techniques that can reduce the reliance on wild populations and ensure the continued viability of eel farming.

Efforts to control eel reproduction in captivity have explored various techniques, including spontaneous spawning and stripping-insemination approaches. These methods aim to enhance breeding success and improve the survival rates of eel larvae (Di Biase et al 2015). However, the success of these techniques has been limited, and they have not yet been widely adopted in commercial operations. The complexity of the eel reproductive cycle, which involves intricate hormonal and environmental triggers, presents significant challenges for researchers and farmers alike.

The process of rearing eels from glass eel to elver is further complicated by the need for specialized diets. Traditionally, eel aquaculture has relied on fishmeal or animal-protein-based feeds to support the growth and development of young eels. However, the high cost and environmental impact of these feeds have led to a search for alternative, more sustainable options. Recent research has explored the use of plant-based protein diets as a potential substitute for traditional fishmeal. These diets have shown promise in supporting the growth of eels, but their impact on the overall health and intestinal maturation of the eels requires further investigation (Dewanti et al 2022).

The process of rearing eels from glass eel to elver is further complicated by the need for specialized diets. Traditionally, eel aquaculture has relied on fishmeal or animal-protein-based feeds to support the growth and development of young eels. Plant-based diets rely on alternative protein sources such as soybean (Liang et al 2023) and pea protein, with added nutritional additives to compensate for lower protein quality. However, due to environmental concerns and the high cost of fishmeal, there is growing interest in sustainable alternatives. Although plant-based diets show promise, their impact on the overall health and intestinal maturation of eels requires further investigation to fully optimize their application in eel aquaculture.

The gender distribution of eels in aquaculture is another important factor that affects the industry. Studies have shown that high rearing densities during the glass eel and elver stages can influence the gender ratio, with higher densities leading to a greater percentage of females (Rachmawati & Sistina 2020). This is particularly significant because female eels are generally more valuable in the market due to their larger size and higher fat content. Techniques such as gender manipulation through dietary supplements, like soy isoflavones, have been explored to induce feminization and increase the proportion of females in aquaculture settings (Inaba et al 2022).

Disease management is another critical aspect of eel aquaculture, especially given the susceptibility of eels to various pathogens. For instance, *Herpesvirus anguillae* has been identified as a significant threat to eel farming operations, particularly in regions like Vietnam, where eel farming involves a multistage process that includes both hatcheries and rearing farms (Panicz et al 2021). The outbreak of diseases not only affects the survival rates of eels but also has economic implications for the industry.

Technological advancements and innovations in eel farming practices are essential for addressing the challenges faced by the industry. For example, the application of

biofloc technology, which allows for high-density farming with minimal water exchange, has shown potential in improving the sustainability and efficiency of eel aquaculture (Vinatea et al 2023). Additionally, the integration of new tools such as Arduino-based fish counters offers promising solutions for monitoring and managing eel populations more effectively (Erten & Özdilek 2018).

Eel aquaculture is a complex and challenging industry that requires careful management of both biological and environmental factors. The reliance on wild-caught juveniles, the lack of large-scale artificial breeding techniques, and the need for sustainable farming practices are critical issues that must be addressed to ensure the long-term viability of the industry. Ongoing research and innovations in breeding, rearing, and disease management are essential for advancing eel aquaculture and reducing its impact on wild populations and the environment.

Challenges in feeding strategies: fishmeal and sustainable alternatives. Feeding strategies for glass eels (*Anguilla* sp.) in aquaculture have long relied on fishmeal-based diets, which are regarded as the standard due to their high protein content and ability to support the rapid growth of juvenile eels. However, recent research has revealed significant challenges associated with these traditional practices, particularly concerning the long-term sustainability and health of the eels.

Fishmeal, while nutritionally rich, poses several challenges when used as the primary diet for glass eels. Studies have shown that prolonged feeding of fishmeal or fish roe to glass eels can negatively impact their growth, metamorphosis, and digestive function. For instance, Gisbert & Mozanzadeh (2019) demonstrated that diets with a high substitution level of plant-based protein can delay intestinal maturation in glass eels. This underscores the need for alternative feeding strategies that can promote healthier and more sustainable growth patterns in eels.

The reliance on fishmeal also raises environmental and economic concerns. Fishmeal production is resource-intensive and often linked to overfishing, contributing to the depletion of wild fish stocks. As global demand for fishmeal increases, so do the prices, making it a less viable option for large-scale aquaculture operations. This economic burden, coupled with the environmental impact, has driven the search for more sustainable alternatives, such as plant-based protein diets.

Environmental factors further complicate feeding strategies. Changes in ocean conditions, such as warming and acidification, have been shown to affect the migration and settlement patterns of glass eels. Borges et al (2019) indicated that these environmental shifts could alter the behaviour of glass eels, potentially impacting their ability to migrate upstream and settle in freshwater habitats. Such changes may influence the success of feeding practices by modifying the physiological and metabolic needs of the eels, requiring adjustments to their diets.

Moreover, the migration and recruitment patterns of glass eels, as observed in regions like the Yangtze Estuary in China, suggest that environmental stressors such as delayed migration can lead to decreased body weight and energy deficits (Guo et al 2024). These deficits pose additional challenges in ensuring that glass eels are in optimal condition for feeding, particularly when transitioning to diets that differ significantly from their natural feed sources.

The challenges in transitioning glass eels to new diets are not only biological but also logistical. In many regions, the management of glass eel fisheries is hindered by incomplete catch data and inconsistent reporting practices. Annida et al (2021) observed that in Indonesian estuaries like Cikaso and Cimandiri, the lack of comprehensive data on glass eel catches complicates efforts to manage these populations sustainably. Effective dietary strategies must therefore be integrated with broader conservation and management efforts to ensure that eel populations remain viable.

In addition to environmental and management challenges, the nutritional aspects of feeding diets remain critical. Research by Liang et al (2023) on American glass eels (*Anguilla rostrata*) emphasized the importance of diet composition in influencing intestinal microbiota and gene expression related to inflammation. The study found that formula diets could significantly alter the gut microbiota of glass eels, which in turn

affects their immune responses and overall health. This highlights the need for a balanced and well-formulated diet that supports both the physical growth and the immune health of the eels.

Furthermore, energy storage strategies and the regulation of lipid metabolism in glass eels are crucial for their successful adaptation to aquaculture conditions. Gaillard et al (2015, 2016) explored regional variations in energy storage strategies and gene regulation associated with lipid metabolism in American glass eels. Their findings suggest that the metabolic needs of glass eels can vary depending on environmental conditions and migration patterns, which in turn influence their dietary requirements. Understanding these variations is essential for developing diets that meet the specific energy needs of glass eels at different life stages.

The challenges in feeding strategies for glass eels are multifaceted, involving environmental, nutritional, and logistical factors. The transition from fishmeal-based diets to more sustainable plant-based alternatives is a critical step in addressing these challenges. However, successful feeding requires a holistic approach that considers the physiological needs of the eels, the impact of environmental changes, and the broader context of eel population management. By integrating these elements, aquaculture practices can be optimized to support the long-term sustainability and health of glass eel populations.

Objective: evaluating plant-based protein diets on growth, survival, and intestinal development of glass eels (Anguilla sp.). The objective of this review is to critically assess the effects of plant-based protein diets on the growth, survival, and intestinal development of glass eels (*Anguilla* sp.). This evaluation is driven by the increasing need to identify sustainable and nutritionally adequate alternatives to traditional fishmeal-based diets in aquaculture. As the aquaculture industry continues to expand, there is mounting pressure to reduce reliance on fishmeal, a resource-intensive and environmentally impactful feed ingredient. The transition from fishmeal to plant-based protein sources presents both opportunities and challenges, particularly in the context of the early life stages of fish such as glass eels.

Plant-based protein diets have garnered significant interest in aquaculture research due to their potential to provide a sustainable alternative to fishmeal without compromising fish health and growth. Previous studies on various fish species have demonstrated that while plant proteins can successfully replace fishmeal to a certain extent, they also induce notable changes in fish physiology, particularly in the digestive system. For instance, research on gilthead seabream (*Sparus aurata*) has shown that long-term feeding with high plant protein diets leads to alterations in inflammatory and immune-related gene expression at the intestinal level (Estruch et al 2018). This suggests that plant proteins, while beneficial in reducing the environmental impact of aquaculture, may require careful formulation and supplementation to prevent adverse effects on fish health.

In the case of glass eels, the transition from a fishmeal-based diet to a plant-based diet is particularly critical due to the species' complex life cycle and delicate early developmental stages. The impact of plant-based diets on the intestinal microbiota and gene expression in fish has also been a focus of recent research. Studies on rainbow trout (*Oncorhynchus mykiss*) and Atlantic salmon (*Salmo salar*) have revealed that dietary plant proteins can influence the gut microbiome and gut transcriptome, with implications for overall fish performance and body composition (Król et al 2016; Michl et al 2017). These findings highlight the potential for plant-based diets to alter the gut environment in ways that could either benefit or hinder the health of glass eels. Therefore, understanding how plant-based proteins interact with the gut microbiome of glass eels is essential for developing diets that support their growth and survival.

Furthermore, the inclusion of specific supplements in plant-based diets may enhance their nutritional value and mitigate potential drawbacks. For example, Yan et al (2019) demonstrated that supplementation with taurine in a plant protein-based diet improved the growth, intestinal immune function, and reduced inflammation in young grass carp (*Ctenopharyngodon idella*). This suggests that similar supplementation

strategies could be employed in glass eel diets to ensure that these plant-based diets meet the nutritional requirements necessary for optimal growth and health.

Additionally, recent research on dietary lysine supplementation has shown promising results in enhancing growth hormone-related gene expression in glass eels, further emphasizing the role of specific amino acids in promoting growth and development (Prayogo et al 2023). The strategic inclusion of essential amino acids, such as lysine, in plant-based diets could therefore play a crucial role in supporting the growth and survival of glass eels during the critical feeding phase.

Another aspect to consider is the overall health status of glass eels when fed plant-based diets. Yu et al (2023) found that dietary plant soot supplementation improved the intestinal health status of farmed American eels (*A. rostrata*), indicating that certain plant-derived ingredients can have positive effects on the gut health of eels. This is particularly important for glass eels, whose intestinal health is directly linked to their ability to thrive in aquaculture environments.

Moreover, epigenetic changes induced by dietary plant ingredients, as observed in zebrafish, suggest that plant-based diets may have long-lasting effects on the intestinal homeostasis and inflammatory responses of fish (Dhanasiri et al 2020). These epigenetic modifications could influence how glass eels adapt to plant-based diets over time, potentially affecting their growth trajectories and survival outcomes.

The objective of this review is to thoroughly evaluate the effects of plant-based protein diets on the growth, survival, and intestinal development of glass eels (*Anguilla* sp.). By integrating findings from various studies, this review aims to provide insights into the potential benefits and challenges of replacing fishmeal with plant-based proteins in glass eel aquaculture. Understanding these effects is crucial for developing sustainable and effective feeding strategies that support the long-term viability of glass eel populations in aquaculture settings.

Material and Method. This narrative review, conducted from June to August 2024, provides a comprehensive analysis of current feeding strategies for glass eels (*Anguilla* sp.), with a specific focus on the use of plant-based protein diets and their impact on growth, survival, and intestinal development. The methodology involved a targeted review of the literature, aiming to synthesize key findings from recent studies and provide insights into emerging trends and research gaps in the field.

Literature search and selection. The literature search was conducted using several academic databases, including Google Scholar, PubMed, and Scopus. The search focused on articles published between 2010-2025, ensuring the inclusion of recent developments in eel aquaculture. The primary keywords used in the search were "glass eels (*Anguilla* sp.)", "feeding strategies", "plant-based protein diets", "growth performance", "digestive system maturation", and "immune response". These keywords were combined using Boolean operators to refine the search and ensure the relevance of the retrieved articles.

Inclusion criteria. The review included a wide range of studies, including experimental research, review articles, and meta-analyses, that addressed the following topics: the effects of different types of diets, particularly plant-based diets; glass eels' growth performance, survival rates, and intestinal development during their early developmental stages; and comparative studies between traditional fishmeal-based diets and plant-based alternatives in eel aquaculture.

Data synthesis. The selected literature was synthesized to identify common findings, highlight variations in research methodologies, and pinpoint areas where further research is needed. Emphasis was placed on studies that provided detailed experimental data and those that offered comprehensive reviews of the current state of knowledge. The synthesis aimed to provide a balanced narrative that captures both the benefits and challenges associated with transitioning to plant-based diets in eel aquaculture.

Critical analysis. In addition to summarizing key findings, the review critically analyzed the methodologies and outcomes of the included studies. This analysis was intended to identify potential biases, methodological limitations, and inconsistencies across studies. The goal was to provide a nuanced understanding of the current research landscape and to offer recommendations for future studies that could address identified gaps.

Scope and limitations. As a narrative review, this article does not attempt to provide an exhaustive systematic analysis of all available literature but rather aims to offer a thorough and integrative overview of the most relevant studies. The review is limited by the availability of recent research on certain aspects of glass eel feeding, particularly regarding the long-term effects of plant-based diets. Future research directions are proposed based on the findings and gaps identified during the review process.

Results and Discussion

Traditional diets: historical use of fishmeal in feeding glass eels. Feeding glass eels (*Anguilla* sp.) with appropriate diets is critical for their development in aquaculture. Historically, natural feeds such as *Tubifex* worms and invertebrates were used before transitioning to artificial diets. Combined with fishmeal, it supported the transition to controlled farm-based diets due to its high protein content and balanced amino acids. However, the reliance on fishmeal has challenges, such as high cost and environmental concerns, leading to the exploration of alternative diets

Researchers have explored pre-feeding diets like *Artemia* and *Daphnia*, which mimic natural prey and improve survival and growth (El Hussieny et al 2016). Additives like yeast-based and marine stimulants have shown positive effects on feeding efficiency (Hancz 2020). These strategies help glass eels adapt to compound diets, supporting better nutrient intake and growth.

Plant-based diets, though more sustainable, provide lower digestibility and nutrient availability compared to fishmeal-based diets (Liang et al 2023). As glass eel populations decline globally, efforts in sustainable feeding practices, such as using plant-based proteins, have gained importance for aquaculture sustainability.

Nutritional requirements for glass eels. The glass eel stage represents a critical juncture in the life cycle of eels. During this phase, eels undergo significant physiological transformations as they migrate from marine environments to freshwater habitats. The successful transition from the ocean to estuaries and further inland migration relies heavily on the nutritional status of the glass eels, which influences their energy reserves, growth, and overall survival (Gaillard et al 2015). As such, understanding and meeting the nutritional requirements during this stage is crucial for supporting their development and ensuring their success in aquaculture settings.

One of the primary nutritional needs of glass eels during this stage is energy, which is vital for sustaining their migration and supporting metamorphosis. The migration process is energy-intensive, and the ability of glass eels to resume feeding and replenish their energy reserves upon reaching estuarine environments is crucial for their continued development (Huisman et al 2023). This energy is primarily derived from lipids, which play a critical role in their metabolic processes. Research has shown that specific fatty acids are selectively transferred and conserved in the ovaries of eels at different stages, indicating the importance of lipid content and composition in their overall development (Gao et al 2018). Therefore, providing a diet rich in essential fatty acids is fundamental to supporting the energy demands of glass eels during this critical stage.

In addition to energy requirements, protein is another essential nutrient necessary for the growth and tissue development of glass eels. The digestive system of glass eels is equipped with enzymes capable of efficiently digesting proteins, carbohydrates, and lipids, with a particular emphasis on protein digestion (Hsu et al 2015). This suggests that a diet with a balanced protein content is necessary to support the rapid growth and developmental processes occurring during this stage. The high levels of amino acid transporters in the digestive system of glass eels further emphasize the importance of

protein in their diet, as these transporters facilitate the uptake of essential amino acids required for various physiological functions (Hsu et al 2015).

The nutritional composition of the diet also influences the hormonal and biochemical processes that regulate development. For instance, the hormonal treatments used to induce vitellogenesis in European eels have been shown to affect the biochemical composition of eggs and yolk-sac larvae, indicating that nutrient utilization patterns vary across developmental stages (Benini et al 2022). This highlights the need for diets that are not only nutritionally balanced but also tailored to meet the specific developmental needs of glass eels during their transition from marine to freshwater environments.

Another important aspect of the nutritional requirements during the glass eel stage is the role of micronutrients and minerals in supporting metabolic functions. The continuous increase in erythrocyte density observed in glass eels as they progress through different stages of development indicates the growing demand for oxygen transport and metabolic activity (Hatakeyama et al 2022). Micronutrients, such as iron, are essential for the production of haemoglobin and the proper functioning of erythrocytes. Thus, ensuring that the diet of glass eels contains adequate levels of these essential micronutrients is critical for maintaining their physiological health and supporting their migratory and developmental processes.

Furthermore, genetic factors play a role in determining the nutritional requirements of glass eels, particularly in relation to growth and head shape dimorphism. Differential gene expression studies in European glass eels have revealed a link between head shape, growth rate, and chemotaxis, suggesting that genetic predispositions may influence the nutritional needs of different morphotypes (Bandara et al 2023). Understanding these genetic influences can help in designing diets that are optimized for the specific needs of glass eels, taking into account variations in growth patterns and developmental processes.

Environmental factors, such as salinity, also impact the nutritional requirements of glass eels. As eels transition from marine to freshwater environments, their ability to tolerate changes in salinity is critical for their survival. Salinity affects various physiological processes, including metabolism, nutrition, and growth, and therefore, the diet of glass eels must be formulated to support their adaptation to changing salinity levels (Cadiz & Traifalgar 2020). This includes providing nutrients that aid in osmoregulation and maintaining electrolyte balance, which are essential for the successful acclimation of glass eels to freshwater habitats.

Moreover, the ecological context in which glass eels develop also influences their nutritional needs. The habitat preferences and genetic adaptations of eels, such as the American eel, during the glass eel stage provide insights into their ecological requirements and survival strategies (Pavey et al 2017). These factors must be considered when formulating diets for glass eels, ensuring that their nutritional needs are met in a way that supports their natural behaviours and ecological roles.

In conclusion, the glass eel stage of *Anguilla* sp. is a period marked by significant nutritional demands, driven by the need for energy, protein, micronutrients, and genetic and environmental adaptations. Meeting these nutritional requirements is essential for supporting the migration, metamorphosis, and overall development of glass eels as they transition from marine to freshwater environments. By understanding and addressing these needs, aquaculture practices can be optimized to enhance the survival and growth of glass eels, contributing to the sustainability of eel populations and the success of aquaculture operations.

Challenges with fishmeal-based diets: sustainability and cost. The use of fishmeal as a primary protein source in aquaculture feeds, particularly in the diets of glass eels (*Anguilla* sp.), has long been a cornerstone of the industry due to its high nutritional value. However, the sustainability and cost associated with fishmeal-based diets have become significant concerns, driving the need for alternative solutions. As the demand for aquafeeds increases globally, the ecological and economic viability of relying solely on fishmeal is increasingly being questioned (Singh & Muthukumarappan 2014, 2016).

Fishmeal is primarily produced from wild-caught forage fish, which are finite resources. The heavy reliance on these wild stocks for fishmeal production has raised environmental concerns, particularly regarding overfishing and the ecological impacts of depleting these fish populations (Hua et al 2019). The sustainability of fishmeal is further compromised by the fact that many forage fish species are essential components of marine food webs, serving as prey for larger fish, seabirds, and marine mammals. The reduction of these stocks for aquafeed production can therefore have cascading effects on marine ecosystems.

The rising cost of fishmeal is another significant challenge. As global fish farming expands, the demand for fishmeal has surged, leading to increased prices. This price escalation makes fishmeal an economically unsustainable option for many aquaculture operations, particularly those in developing regions where cost constraints are a major concern (Singh & Muthukumarappan 2016). The high protein and phosphorus content in fishmeal-based feeds also poses challenges for the sustainability of aquaculture systems, as it can lead to excessive nutrient loading in aquatic environments, contributing to water quality degradation (Raza et al 2025).

To address these challenges, the aquaculture industry is increasingly exploring alternative protein sources that can replace or supplement fishmeal in aquafeeds. Soybean meal, for instance, has emerged as a viable alternative due to its high protein content and favourable amino acid profile. Research has shown that fermented soybean meal can partially replace fishmeal in diets without compromising growth or health in various fish species (Pratiwy & Triyani 2022). The use of insect meal, microalgae, and other novel protein sources is also gaining traction as sustainable and cost-effective alternatives (Ang et al 2021; Bera et al 2022). These ingredients offer the potential to reduce the environmental footprint of aquaculture while maintaining the nutritional quality of feeds.

In addition to plant-based and novel protein sources, functional feed additives are being incorporated into aquafeeds to enhance their nutritional value and reduce reliance on fishmeal. These additives, which include prebiotics, probiotics, and other bioactive compounds, can improve feed efficiency, promote gut health, and enhance the overall performance of farmed fish (Badguzar et al 2024). The inclusion of such ingredients not only makes feeds more environmentally friendly but also helps in achieving better growth rates and feed conversion ratios, further reducing the economic burden on aquaculture operations.

Innovative approaches to aquafeed formulation are also being explored to enhance sustainability. Feather meal and rendered animal by-products, for example, are being used as alternative protein sources in aquafeeds (Jasour et al 2017). These materials, which are by-products of other industries, offer a way to recycle nutrients and reduce waste, aligning with the principles of circular economy and sustainability. Eco-organic feeds, which are designed to minimize environmental impacts and enhance nutrient retention, represent another promising avenue for sustainable aquaculture (Tefal et al 2023).

Despite the potential benefits of these alternatives, there are challenges that need to be addressed to ensure their successful integration into aquaculture systems. The digestibility and palatability of plant-based proteins, for example, can differ from those of fishmeal, potentially affecting the growth and health of farmed fish. Additionally, the amino acid profiles of alternative proteins may not always match the nutritional requirements of certain fish species, necessitating careful formulation and supplementation to avoid deficiencies.

In conclusion, the challenges associated with fishmeal-based diets, including sustainability and cost, underscore the need for the aquaculture industry to diversify its protein sources and adopt more sustainable feeding practices. By exploring and integrating alternative proteins such as soybean meal, insect meal, and microalgae, as well as utilizing functional feed additives and innovative feed formulations, the industry can reduce its reliance on fishmeal, lower costs, and mitigate environmental impacts. These efforts are crucial for the long-term viability of aquaculture, particularly in

supporting the growth and development of glass eels and other farmed species in a sustainable manner.

***Development of plant-based diets for glass eels (Anguilla* sp.*)*.** The shift to plant-based diets in aquaculture, especially for glass eels, marks a critical step toward sustainable feeding practices. Historically, fishmeal has been the primary protein source due to its high nutritional value. However, rising costs and environmental concerns have driven the exploration of alternatives, with plant-based proteins such as soybean gaining traction.

Key challenges include ensuring plant-based diets support intestinal health and maturation, crucial for efficient nutrient absorption. Research shows that these diets can impact gut microbiota, which is vital for the growth of glass eels (Liang et al 2023). Fermentation techniques help improve plant protein digestibility, making the diets more suitable by breaking down complex compounds and enhancing gut health (Mugwanya et al 2023).

Lessons from other sectors, such as animal husbandry, highlight the importance of careful management during the transition to plant-based diets to prevent stress and promote adaptation (Ndjadi et al 2021; Dos Santos Neves et al 2024). Nutritional strategies that maintain gut integrity are critical for minimizing adverse effects and ensuring long-term health (Colombino et al 2021). The rise of plant-based proteins represents a move toward more sustainable aquaculture, requiring a multidisciplinary approach to meet the nutritional needs of glass eels while promoting long-term population viability.

Nutritional composition of plant-based diets for glass eels: key ingredients and nutritional adequacy. The nutritional composition of plant-based diets plays a central role in supporting the health and development of glass eels. Proper formulation is essential to ensure that these diets meet protein and lipid requirements. Research highlights that the protein and lipid content of plant-based diets significantly influences intestinal maturation and gut microbiota (Liang et al 2023). Common protein sources include soybean meal and pea protein, both rich in essential amino acids, but requiring supplementation to address potential deficiencies in methionine and lysine.

Lipids, particularly essential fatty acids, are vital for energy and physiological functions. Plant oils like flaxseed and canola can provide omega-3 and omega-6 fatty acids, though careful balance is needed to match marine oils' benefits. Additionally, micronutrients such as vitamins and minerals must be included to prevent deficiencies and support metabolic processes (Dhanasiri et al 2020).

Functional additives like prebiotics and probiotics further enhance nutrient absorption and gut health, ensuring plant-based diets meet the nutritional needs of glass eels (Politis et al 2023). The overall goal is to create balanced diets that reduce reliance on fishmeal while supporting growth and health.

***Growth performance: comparison of plant-based and traditional diets in glass eels (Anguilla sp.)*.** The shift toward plant-based diets in glass eel aquaculture aims to address sustainability and rising costs of fishmeal. Plant-based diets can support growth, they may delay intestinal maturation compared to fishmeal-based diets, which provide superior growth rates and survival percentages. Careful formulation and supplementation of plant-based diets, such as with lysine and probiotics, are necessary to enhance digestion and growth.

Plant-based diets reduce reliance on fishmeal but require enhancement to match fishmeal-based diet outcomes. Research on species like seabream indicates that prolonged plant-based diets may affect immune responses, further emphasizing the need for optimization (Estruch et al 2018).

Survival rates: effects of different diets on glass eels. Survival rates are a critical metric in evaluating dietary regimes in glass eel aquaculture. Research by Benini et al (2023) demonstrates that diet composition significantly impacts survival, with specific

diets yielding higher survival rates and better growth outcomes. Mixtures of pellets and live feeds like *Tubifex* worms have also shown promise, improving survival rates by stimulating natural feeding behaviors (Diansyah & Marlian 2016).

Morphological factors, such as cranial shape, can influence feeding efficiency, which may also affect survival outcomes (Bandara et al 2023). Feeding frequency and water quality management are equally crucial, as optimal feeding schedules and environmental conditions directly correlate with survival (Harianto et al 2021). High mortality rates in eel cultivation highlight the need to optimize both dietary and environmental factors to improve survival.

Metamorphosis and development: impact of diet on the transition to elvers. The transition from glass eels to elvers involves significant physiological and morphological changes. Diet plays a critical role in this metamorphosis, particularly in influencing intestinal maturation and enzyme activity. Plant-based diets alter enzymes like alkaline phosphatase (AP) and leucine aminopeptidase (LAP), which are essential for nutrient absorption.

Lipid metabolism and storage, regulated by dietary factors, are also crucial during this energy-intensive phase (Gaillard et al 2016). Behavioral adaptations, such as response to conspecific odor cues, are influenced by diet, as glass eels transition to foraging behaviors suitable for elvers (Schmucker et al 2016).

Thyroid function and diet-induced phenotypic plasticity, such as changes in pigmentation and cranial morphology, further underscore the importance of a well-balanced diet during this transition (Sudo et al 2014; Bandara et al 2023). Proper dietary management ensures healthy development, promoting successful metamorphosis and long-term viability in aquaculture.

Digestive system development: impact of diet on digestive maturation in glass eels (Anguilla sp.). The development of the digestive system in glass eels is a critical aspect of their growth and survival in aquaculture. The transition from natural feeding patterns to controlled diets, particularly with the introduction of plant-based proteins, significantly influences the maturation of their digestive system.

While plant-based diets provide a more sustainable alternative to fishmeal, they may require careful formulation to ensure that the maturation process is not delayed. Delayed maturation could compromise the eels' growth and overall health, as their ability to efficiently digest and absorb nutrients is essential for survival in controlled environments.

Dietary supplements such as probiotics and taurine have been found to mitigate some of the digestive limitations associated with plant-based diets. Probiotics, in particular, enhance the diversity of gut microbiota, which plays a pivotal role in nutrient absorption and gut health. Similarly, taurine (Yan et al 2019) has been shown to reduce gut inflammation and promote muscle development, thus supporting both digestive health and overall growth.

Supplements such as probiotics and taurine offer additional benefits beyond basic nutrition, supporting intestinal health and overall survival rates. Their inclusion in plant-based diets for glass eels can significantly improve digestive efficiency and general well-being, helping to overcome the limitations inherent in plant-based formulations.

The role of microbial populations within the gut is also a major factor in digestive system development. Studies, such as of Jang et al (2022), indicate that probiotics, such as *Bacillus* species, enhance survival rates and intestinal health by influencing the composition of gut microbiota. The introduction of beneficial microorganisms can further support the maturation of the digestive system, ensuring that glass eels efficiently process nutrients from alternative diets.

In conclusion, the maturation of the digestive system in glass eels is profoundly affected by diet composition and the inclusion of functional supplements. While plant-based diets present sustainable alternatives to fishmeal, careful formulation - including the use of probiotics and other supplements - is necessary to support digestive health and ensure optimal growth and survival.

Enzyme activity: impact of diet on pancreatic and intestinal enzyme activities. Pancreatic and intestinal enzymes are central to the digestive processes of glass eels, particularly as their digestive systems mature. The activity of these enzymes is strongly influenced by dietary composition, especially when transitioning from traditional fishmeal-based diets to plant-based alternatives. Key enzymes such as alkaline phosphatase (AP) and leucine aminopeptidase (LAP) are crucial for the breakdown of proteins and other nutrients, with their activity levels serving as markers of digestive efficiency.

The need to balance lipid composition in plant-based diets is another critical factor affecting pancreatic enzyme activity. Kowalik et al (2018) showed that the inclusion of specific lipid sources, such as rapeseed and linseed oils, in aquafeeds modulates bile secretion and enzyme activity. This suggests that fine-tuning the types of oils included in plant-based diets could enhance pancreatic function, promoting better digestion and nutrient absorption.

In conclusion, the activity of pancreatic and intestinal enzymes is a crucial determinant of nutrient utilization in glass eels. While plant-based diets present a viable alternative to fishmeal, their impact on enzyme activities necessitates careful formulation and supplementation to optimize digestive efficiency and ensure healthy growth in glass eels.

Long-term effects: early diet and its lasting impact on digestive efficiency and health. The early diet of glass eels has lasting implications for their digestive efficiency and overall health throughout their life cycle. The concept of nutritional programming suggests that early exposure to specific diets can have enduring effects on metabolism, growth, and nutrient utilization. Research by Inoue et al (2023) on medaka fish, for example, shows that early dietary interventions lead to epigenetic changes that influence gene expression and metabolic pathways in the long term.

In the context of glass eels, early exposure to plant-based diets could condition their digestive systems to process plant proteins more efficiently, reducing dependence on fishmeal in later stages of development. However, if early diets fail to support optimal digestive enzyme activity and nutrient absorption, this may result in long-term deficits in growth and health.

Muscle development is another area where early dietary interventions can have profound effects. Studies on other fish species, such as by Alami-Durante et al (2014), show that early nutritional reductions can alter muscle growth mechanisms. For glass eels, early diets that are insufficient in key nutrients may hinder muscle development and overall growth potential.

The early diet plays a pivotal role in shaping the long-term digestive efficiency and health of glass eels. Early exposure to well-formulated, nutrient-dense diets ensures that digestive capabilities are established, promoting growth and reducing health risks throughout the eel's life cycle. Careful management of early dietary interventions, particularly with plant-based proteins, is essential to ensure the long-term success of aquaculture practices.

Immune response: influence of diet on immune-related gene expression in glass eels (Anguilla sp.). Diet profoundly affects immune-related gene expression in glass eels. Immune function is crucial in determining the ability of glass eels to resist pathogens, and dietary composition can significantly modulate these immune responses at the molecular level. Bandara et al (2023) showed a connection between diet, morphology, and immune-related gene expression in glass eels, linking dietary shifts with changes in growth rate, head shape, and chemotaxis, a key aspect of immune cell migration.

Additionally, Benini et al (2023) found that different first-feeding diets in European eel larvae induced significant changes in immune gene expression, indicating the influence of diet on the development of immune responses. The modulation of immune genes by diet extends beyond nutrition, impacting the long-term health and survival of eels in aquaculture.

Dietary supplements may further enhance immune responses. Guo et al (2020) and Guo et al (2024) demonstrated how immunization with recombinant proteins from *Aeromonas hydrophila* modulated immune gene expression in eels, suggesting that well-formulated diets could enhance immune protection. In summary, optimizing plant-based diets to support robust immune-related gene expression is vital for improving disease resilience in glass eels, ensuring better survival and overall health in aquaculture environments. Effective dietary management ensures the long-term health and productivity of glass eels in aquaculture.

Role of plant-based diets in promoting sustainable eel farming practices. Sustainability is becoming a core objective in aquaculture, with eel farming historically relying on wild-caught eels and fishmeal-based diets that are tied to environmental degradation and overfishing. The industry's shift toward plant-based proteins as an alternative to fishmeal is a significant move towards addressing these challenges. This transition provides an opportunity to reduce reliance on finite marine resources and to promote more sustainable aquaculture practices.

Fishmeal, traditionally a cornerstone in aquafeeds, is derived from wild-caught fish stocks, which are increasingly being depleted. This dependence on marine resources raises concerns not only about overfishing but also about the long-term viability of eel farming. Plant-based diets, on the other hand, offer a more sustainable alternative. Plant proteins such as soybean meal, microalgae, and other plant-based ingredients have shown promise as replacements for fishmeal. Moreover, these plant-based diets may help reduce the industry's environmental footprint.

Beyond feed components, the environmental impact of eel farming extends to the use of synthetic materials such as nylon cages and polyethylene films, which contribute to microplastic pollution in aquaculture systems (Lv et al 2020). Transitioning to more environmentally friendly practices through the adoption of plant-based diets is an important step, not only for reducing the environmental footprint but also for addressing issues like microplastic contamination.

Moreover, sustainability in aquaculture encompasses more than just feed alternatives. Disease management is also critical in ensuring sustainable practices. *Herpesvirus anguillae*, for instance, has been identified as a major threat to farmed European eels, particularly in environments where farmed and wild populations mix (Nguyen et al 2017). Managing these interactions and preventing the spread of disease is crucial for maintaining the health of both farmed and wild populations. In regions where wild and farmed eels coexist, the presence of wild eels can increase the likelihood of disease transmission, making biosecurity measures essential for sustainability.

Furthermore, the interaction between wild and farmed eels in shared environments has been a subject of concern. Studies have shown that agonistic behaviours between wild and farmed eels in mixed-rearing environments can negatively affect growth and survival rates in farmed populations (Wakiya et al 2022). This emphasizes the need for carefully managed environments that minimize the potential for negative interactions between these groups. Additionally, interventions such as stocking farmed eels in rivers with high densities of wild eels have yielded mixed results. Farmed eels often exhibit slower growth rates in these environments, raising questions about the efficacy of these stock enhancement practices.

Plant-based diets play a pivotal role in promoting sustainable aquaculture practices in eel farming. However, challenges remain in ensuring that these diets are nutritionally adequate for the species' development, and further consideration must be given to disease management, environmental impacts, and interactions between farmed and wild populations. The future of sustainable eel farming will require a holistic approach that integrates ecological, economic, and technological advancements to reduce environmental impacts and promote the long-term viability of the industry.

Cost-benefit analysis of plant-based diets in commercial eel farming. The transition from fishmeal-based diets to plant-based alternatives in commercial eel farming offers significant economic advantages, primarily through cost reductions and the

stabilization of feed supply. Fishmeal, while nutritionally superior, is expensive and subject to supply fluctuations due to overfishing and environmental concerns. In contrast, plant-based ingredients such as soybean meal and microalgae present more cost-effective and sustainable options. This economic shift is crucial, given the rising costs associated with traditional fishmeal and the increasing global demand for aquafeeds.

The potential for plant-based diets to provide economic benefits has been demonstrated in several studies. Kim et al (2020), for example, showed that substituting fishmeal with alternative protein sources in Korean rockfish (*Sebastes schlegeli*) diets not only maintained growth performance but also improved economic efficiency. These findings are significant for eel farming, where the high cost of fishmeal constitutes a major operational expense. By reducing reliance on fishmeal, eel farmers can achieve lower production costs without compromising on growth outcomes.

Furthermore, Choi et al (2020) demonstrated that olive flounder reared on diets incorporating both plant and animal protein sources achieved comparable growth and health outcomes to those fed traditional fishmeal-based diets. These results suggest that similar approaches could be applied to eel farming, where cost savings can be realized through the incorporation of plant proteins while maintaining the nutritional balance necessary for optimal growth and survival.

Additionally, global trends in the availability of plant-based ingredients are expected to drive down costs further. Sandström et al (2022) noted that the increased availability of plant-based biomass could significantly lower feed costs for aquaculture operations worldwide. This is particularly relevant in regions where the cost of fishmeal is prohibitive, making plant-based diets an economically attractive option. Furthermore, the transition to plant-based diets aligns with broader trends in sustainable agriculture, as demonstrated by Miljatović & Vukoje (2024), who applied an opportunity cost approach to measure the economic viability of farms in Serbia, showing that plant-based farming tends to be more profitable and sustainable compared to livestock farming.

However, the adoption of plant-based diets in commercial eel farming is not without challenges. Macusi et al (2023) cautioned that while plant proteins can replace fishmeal, their nutritional content must be carefully balanced to prevent deficiencies. Essential amino acids, such as lysine and methionine, are often lacking in plant-based feeds, which may necessitate supplementation to achieve the same growth rates as traditional fishmeal-based diets. In this context, ongoing research into diet formulations that optimize the nutritional profiles of plant-based feeds is essential for ensuring the economic viability of these diets in commercial settings.

The economic viability of plant-based diets in eel farming is promising, with clear cost savings and environmental benefits. However, success will depend on continued research and refinement of these diets to ensure they meet the nutritional needs of eels while maintaining competitive growth rates and feed efficiency. By adopting plant-based diets, commercial eel farms can reduce production costs, stabilize feed supply, and align with sustainable aquaculture practices.

Optimizing diet formulations and their impact on eel development. As the aquaculture industry moves towards more sustainable practices, future research on diet formulations for eels will be essential to fully understand and optimize the impact of plant-based diets on growth, survival, and overall development. Several critical areas need further exploration to improve the effectiveness of plant-based diets and ensure the sustainability of eel farming.

The role of fatty acids, particularly the balance of n-3 and n-6 fatty acids, is another area requiring further investigation. Butts et al (2015) underscored the importance of these fatty acids in reproductive performance and overall health, suggesting that optimizing the fatty acid profiles in plant-based diets could significantly enhance eel growth and reproductive success. Similarly, Kontara et al (2023) suggested that refining the fatty acid composition in commercial diets for Indonesian shortfin eels could greatly improve their growth and health outcomes.

In addition to fatty acids, amino acids play a crucial role in the development and reproductive success of eels. Butts et al (2020) demonstrated that dietary amino acids

influence sperm performance traits in European eels, highlighting the need for further research into how amino acid supplementation could optimize growth and reproductive outcomes in farmed eels.

Furthermore, the inclusion of feeding stimulants in diets has shown potential in improving feed acceptance and growth. Hirt-Chabbert et al (2012) suggested that the use of feeding stimulants could enhance feed intake and growth, particularly during critical developmental phases when eels are transitioning from natural diets to formulated feeds. This approach could prove especially useful in making plant-based diets more palatable and effective, given their lower natural palatability compared to fishmeal-based diets.

Environmental factors, such as feeding habitats and exposure to environmental micropollutants, also need to be considered in future research. Parzanini et al (2021) noted that the feeding habitat and silvering stage of European eels significantly influence their lipid content and fatty acid composition. These findings indicate that diet formulations must account for the environmental conditions in which eels are raised, as these factors can affect their nutritional needs and overall health.

Finally, research into the effects of environmental micropollutants on eel gut microbiota could provide valuable insights into how diet and environmental factors interact to influence eel health. Bertucci et al (2022) found that diet composition and environmental pollutants together impact the gut microbiota of wild European eels, suggesting that future diet formulations should consider the potential effects of environmental stressors on eel health.

In conclusion, future research on eel diet formulations should prioritize optimizing fatty acid and amino acid profiles, exploring the use of feeding stimulants, and considering environmental factors that affect eel development. By addressing these areas, researchers can develop more effective and sustainable diets that support the growth, health, and reproductive success of farmed eels, ultimately contributing to the long-term sustainability and economic viability of eel aquaculture.

Key insights on plant-based diets for glass eels (Anguilla sp.). This review has explored the transition from fishmeal-based to plant-based diets in glass eel (*Anguilla* sp.) aquaculture, highlighting significant insights and challenges that must be addressed to optimize eel farming practices.

The move toward plant-based diets is driven by the need for sustainability and cost reduction. Fishmeal, traditionally used in aquaculture, faces supply challenges and ecological concerns due to overfishing. Plant-based alternatives like soybean meal and microalgae offer more sustainable and potentially less expensive options

One key finding is that while plant-based diets can support comparable growth rates to fishmeal diets, nutrient balancing is essential. Supplementation of specific amino acids and fatty acids is often required to avoid deficiencies and ensure optimal development. Additionally, functional additives such as antioxidants can mitigate oxidative stress, as highlighted by studies like Abozaid et al (2023), which showed the positive impact of *Spirulina* on immune responses.

Long-term implications of early diet choices are critical. The concept of nutritional programming, as discussed by Inoue et al (2023), indicates that early dietary interventions can have lasting effects on growth potential, metabolic pathways, and health outcomes in glass eels. Early exposure to well-formulated diets can promote better digestive efficiency and resilience to stressors later in life, emphasizing the need for careful management of early nutrition.

In terms of economic viability, the adoption of plant-based diets presents significant cost-saving opportunities while aligning with sustainability goals. Research from Sandström et al (2022) and Miljatović & Vukoje (2024) suggests that plant-based biomass production is increasing globally, which could further reduce feed costs. However, ongoing research and adjustments in diet formulation are needed to ensure that these diets meet the eels' nutritional demands without compromising growth or health.

Plant-based diets offer a promising solution for sustainable eel aquaculture. However, achieving success requires precise diet formulation, careful management of early life nutrition, and continued research to optimize both economic and environmental outcomes.

Potential of plant-based diets in eel farming. The integration of plant-based diets into glass eel aquaculture carries important implications for sustainability, economic efficiency, and long-term eel health. The shift away from fishmeal addresses growing concerns about the depletion of marine resources and the rising costs associated with fishmeal production.

Plant-based diets, when formulated correctly, can significantly reduce the environmental impact of aquaculture. Fishmeal, derived from wild-caught fish, has raised sustainability concerns due to overexploitation of marine stocks. By transitioning to renewable, plant-based alternatives, eel farming can mitigate its environmental footprint while contributing to global efforts in promoting sustainable aquaculture (Kim et al 2020).

In terms of economic viability, plant-based proteins like soybean meal present a cost-effective alternative. Studies such as those by Choi et al (2020) have shown that fishmeal can be replaced with plant proteins without sacrificing growth performance. Furthermore, the increasing global production of plant-based biomass will likely continue to lower costs, making these diets more attractive to eel farmers (Sandström et al 2022).

However, challenges remain in ensuring that plant-based diets meet the nutritional needs of glass eels. Proper supplementation with essential nutrients such as amino acids and fatty acids is required to avoid deficiencies that could impair growth and health (Butts et al 2020). Early dietary interventions also have lasting impacts on metabolic pathways and growth potential, as discussed by Prayogo et al (2023). This underscores the importance of ongoing research into nutritional programming to ensure long-term viability in eel farming.

Overall, the potential for plant-based diets to replace traditional fishmeal in eel aquaculture is significant. Careful management and refinement of these diets will be critical to ensuring that they meet the health and nutritional needs of eels, while also contributing to the sustainability and economic viability of the industry.

Importance of continued research. The future of eel aquaculture depends on continued research into diet formulation, environmental management, and larval development. Addressing the challenges of feeding and breeding eels in captivity is essential for reducing dependence on wild populations and promoting sustainable practices.

One of the most important areas for future research is the optimization of early dietary regimes, particularly in larval stages. Benini et al (2023) emphasized the importance of refining diets to enhance early growth and survival. Additionally, the role of fatty acids in reproduction and health, as highlighted by Butts et al (2015), remains a critical area for study. Research on amino acid supplementation and feeding stimulants will also be necessary to improve diet palatability and growth outcomes, as suggested by Hirt-Chabbert et al (2012).

Environmental factors, such as feeding habitats and exposure to micropollutants, must also be considered. The interaction between diet and environmental conditions can significantly impact eel health and development, as seen in studies by Bertucci et al (2022). Understanding these interactions will enable more effective management of both diet and environmental factors in aquaculture systems.

Additionally, advancements in hatchery technology and breeding are crucial for the future of eel farming. Efforts to cryopreserve spermatozoa and improve reproductive success in hatcheries are key to reducing reliance on wild-caught juveniles (Herranz-Jusdado et al 2019). Exploring alternative eel species for aquaculture, such as giant-mottled and shortfin eels, will also contribute to the resilience and diversification of the industry (Hsu et al 2018). Continued research into diet formulation, breeding technologies, and environmental management will be essential for ensuring the sustainability and success of eel aquaculture. By addressing these challenges, the

industry can move towards more sustainable practices that meet global demand while protecting wild eel populations.

Conclusions. This review highlights the potential of plant-based diets as sustainable alternatives to traditional fishmeal in glass eel (*Anguilla* sp.) aquaculture. The findings demonstrate that while plant-based diets offer significant environmental and economic benefits, their successful implementation requires careful formulation to meet the nutritional needs of eels. Key challenges include ensuring proper protein and lipid content, as well as balancing essential amino acids and fatty acids to support intestinal maturation, growth, and immune function.

Studies indicate that plant-based diets can support comparable growth rates and survival to fishmeal-based diets, but supplementation with functional additives such as probiotics, taurine, and antioxidants is essential to enhance gut health and nutrient absorption. Moreover, early dietary interventions can have long-term effects on digestive efficiency, growth potential, and overall health, underscoring the importance of nutritional programming during the early stages of development.

The transition to plant-based diets is also aligned with broader sustainability goals, offering a pathway to reduce reliance on marine resources and mitigate the environmental impact of eel farming. However, ongoing research and optimization of these diets are crucial to ensure their effectiveness in commercial eel aquaculture. By addressing these challenges and refining diet formulations, the aquaculture industry can promote sustainable and economically viable practices that support the long-term health and productivity of farmed eel populations.

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Authors:
Endhay Kusnendar Muljana Kontara, Research Center for Fisheries, National Research and Innovation Agency of Indonesia (BRIN), Jakarta-Bogor Street, Km. 46, Cibinong, West Java, Indonesia, e-mail: endh001@brin.go.id
Lusi Herawati Suryaningrum, Research Center for Applied Zoology, National Research and Innovation Agency of Indonesia (BRIN), Jakarta-Bogor Street, Km. 46, Cibinong, West Java, Indonesia, e-mail: lusi006@brin.go.id
Adang Saputra, Research Center for Fisheries, National Research and Innovation Agency of Indonesia (BRIN), Jakarta-Bogor Street, Km. 46, Cibinong, West Java, Indonesia, e-mail: adan004@brin.go.id
Siti Murniasih, Research Center for Fisheries, National Research and Innovation Agency of Indonesia (BRIN Jakarta-Bogor Street, Km. 46, Cibinong, West Java, Indonesia, e-mail: siti098@brin.go.id
Lies Emmawati, Research Center for Fisheries, National Research and Innovation Agency of Indonesia (BRIN), Jakarta-Bogor Street, Km. 46, Cibinong, West Java, Indonesia, e-mail: lies005@brin.go.id
Taukhid Taukhid, Research Center for Fisheries, National Research and Innovation Agency of Indonesia (BRIN), Jakarta-Bogor Street, Km. 46, Cibinong, West Java, Indonesia, e-mail: tauk001@brin.go.id
Edy Barkat Kholidin, Research Center for Fisheries, National Research and Innovation Agency of Indonesia (BRIN), Jakarta-Bogor Street, Km. 46, Cibinong, West Java, Indonesia, e-mail: edyb001@brin.go.id
Yohanna Retnaning Widyastuti, Research Center for Fisheries, National Research and Innovation Agency of Indonesia (BRIN), Jakarta-Bogor Street, Km. 46, Cibinong, West Java, Indonesia, e-mail: yoha016@brin.go.id
Abidin Nur II, Research Center for Fisheries, National Research and Innovation Agency of Indonesia (BRIN), Jakarta-Bogor Street, Km. 46, Cibinong, West Java, Indonesia, e-mail: abid006@brin.go.id

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