

Reimagining Salmon Supply Chains: A Sustainability Comparison of 3D-Printed and Traditional Production

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Abstract: The seafood industry faces growing sustainability challenges, including overfishing, resource inefficiency, and environmental degradation, necessitating innovative production alternatives. While traditional SCs benefit from established infrastructure and consumer trust, their high resource demand and operational inefficiencies highlight the need for sustainable alternatives. This study compares traditional and 3D-printed salmon SCs, using process mapping by flowcharting and sustainability metrics to evaluate their environmental, economic, and social impacts. Findings indicate that 3D-printed salmon reduces carbon emissions by up to 86% and freshwater consumption by 95%, primarily by eliminating farming, feed production, and long-distance cold storage. Additionally, localized production lowers logistical costs and enhances resource efficiency. Despite challenges related to consumer acceptance, regulatory approval, and scalability, 3D printing presents a promising complement to aquaculture, supporting long-term sustainability in seafood production.

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1. INTRODUCTION

The rising global population, coupled with mounting environmental concerns, underscores the urgent need for sustainable food production systems. The seafood industry, particularly salmon aquaculture, faces intense scrutiny due to its environmental footprint, including overfishing, high resource consumption, and waste generation (Kelling et al., 2023). These challenges necessitate innovative production approaches that not only meet market demand for high-quality seafood but also align with sustainability objectives.

Norway, the leading producer of farmed Atlantic salmon, has set industry benchmarks in efficiency, quality, and environmental stewardship. Its aquaculture sector is distinguished by advanced practices, stringent regulations, and robust cold chain logistics, making it an ideal model for assessing sustainability in seafood supply chains (SCs) (*Top Salmon Exports & Imports by Country 2023*, n.d.). Despite these advancements, traditional salmon farming remains resource-intensive, requiring significant freshwater inputs, feed derived from marine ecosystems, and extensive energy use for farming, processing, and transportation.

Recent advancements in food technology, particularly 3D printing, present transformative opportunities for addressing inefficiencies in traditional seafood SCs. As an additive manufacturing technique, 3D printing enables precise control over ingredient composition, reduces production waste, and offers scalability for customized food products (Boland, 2008). When applied to salmon production, 3D printing

utilizes plant-based or cultured proteins to replicate the texture, flavor, and nutritional composition of conventional salmon, aligning with rising consumer preferences for sustainable and ethical food alternatives (*'Fishless Fish': The next Big Trend in the Seafood Industry*, 2022).

Compared to traditional salmon SCs—characterized by long production cycles, energy-intensive farming, and complex global logistics—3D-printed salmon presents a streamlined, efficient alternative. By eliminating aquaculture, shortening transportation distances, and enhancing production precision, this technology addresses key sustainability concerns while offering cost advantage and market adaptability. However, challenges such as consumer acceptance, regulatory considerations, and technological scalability must be addressed to realize its full potential.

This study investigates the comparative sustainability of traditional and 3D-printed salmon SCs through process mapping by flowcharting and sustainability metrics. The research evaluates key differences in resource utilization, waste management, and environmental impact, with the aim of determining whether 3D printing can serve as a viable complement or alternative to conventional aquaculture.

This study provides both theoretical and practical contributions. From a theoretical perspective, it examines how 3D printing technology can enhance sustainability within the seafood sector by reducing carbon footprints, optimizing resource efficiency, and streamlining SCs. Practically, it provides a comparative analysis of conventional and 3D-

printed salmon production models, offering insights into the feasibility of integrating 3D printing into existing seafood supply networks. Rather than entirely replacing traditional systems, this study positions 3D printing as a potential disruptor that can create new market opportunities and contribute to long-term industry sustainability.

2. LITERATURE REVIEW

A comparative analysis of traditional and 3D-printed salmon SCs requires an understanding of their respective structures, challenges, and sustainability implications. This section reviews existing research on traditional salmon aquaculture, the emerging role of 3D printing in food production, and the relative strengths and limitations of each system.

2.1 Traditional salmon SC

The traditional salmon SC encompasses multiple interconnected stages, including farming, processing, packaging, and distribution. This system is resource-intensive and has significant environmental impacts, such as high energy use, waste generation, and greenhouse gas emissions (De et al., 2024). While aquaculture has increased global salmon production, concerns persist regarding water pollution, excessive antibiotic use, and the depletion of wild fish stocks for feed (Kelling et al., 2023).

Despite technological advancements, inefficiencies remain within traditional SCs. Long transportation distances between production sites and consumer markets contribute significantly to the carbon footprint. Cold chain logistics—relying on energy-intensive refrigeration and storage—exacerbate environmental concerns (*The Chill Chain Journey of Salmon*, 2021). Additionally, the complexity of the global supply network, involving multiple intermediaries, often results in higher costs, increased waste, and logistical inefficiencies.

Norway, a global leader in salmon aquaculture, has made strides in mitigating these sustainability challenges. Strict regulatory frameworks enforce sustainable feed sourcing, optimized fish densities, and advanced waste management practices (Iversen et al., 2020). However, the fundamental resource intensity of traditional salmon farming necessitates the exploration of alternative production methods that minimize environmental impact while ensuring economic viability.

2.2 3D-printed salmon SC

The integration of 3D printing into food production has gained traction as a potential disruptor to conventional SCs. This technology, also known as additive manufacturing, enables on-demand, localized production, thereby reducing waste, enhancing resource efficiency, and lowering environmental footprints (Sun et al., 2018).

In the context of salmon production, 3D printing replicates the texture, flavor, and nutritional composition of conventional salmon using plant-based proteins, algae, or cultivated cells (*Home - Revo Foods*, n.d.). One of its key advantages is the simplification of the supply chain, reducing reliance on intermediaries and eliminating the farming stage. By sourcing raw materials locally and manufacturing products closer to

consumer markets, 3D-printed seafood drastically cuts transportation-related emissions (Sun et al., 2020).

Additionally, additive manufacturing supports sustainability by repurposing underutilized materials, such as fish skins and bones, into edible products (Jia et al., 2016). Compared to traditional aquaculture, 3D printing significantly reduces water and energy consumption, contributing to a more circular economy (Zhong et al., 2023). However, the widespread adoption of this technology faces challenges, including regulatory uncertainty, scalability limitations, and consumer skepticism regarding taste and authenticity.

2.3 Comparative Insights

A direct comparison between traditional and 3D-printed salmon SCs highlights trade-offs between environmental impact, economic feasibility, and consumer acceptance. While the traditional SC benefits from established infrastructure, market trust, and large-scale production capacity, its environmental footprint and inefficiencies necessitate innovation. Conversely, the 3D-printed SC offers a more sustainable and flexible alternative yet faces technological and regulatory barriers to adoption.

This literature review underscores the potential complementarity of 3D printing in addressing the sustainability challenges of traditional aquaculture.

3. METHODOLOGY

This study adopts a comparative approach to evaluate the sustainability of traditional and 3D-printed salmon SCs. By utilizing process mapping by flowcharting and sustainability metrics, the research aims to identify key differences in resource utilization, environmental impact, and economic feasibility. The methodological framework is designed to provide both theoretical insights into SC sustainability and practical guidance for integrating 3D printing into seafood SCs.

3.1 Process mapping by flowcharting

Process mapping by flowcharting was used to visualize and compare the operational workflows of traditional and 3D-printed salmon SCs using flowcharts, highlighting key differences in production stages, resource utilization, and logistical complexity. The traditional SC map includes stages such as aquaculture, processing, packaging, cold chain logistics, and global distribution. In contrast, the 3D-printed SC map focuses on raw material sourcing, bio-ink preparation, printing, and localized distribution. These maps serve as analytical tools to examine:

- Resource consumption (e.g., water, feed, energy),
- Waste generation and management,
- Carbon footprint from transportation and logistics,
- Process efficiencies and operational bottlenecks.

By highlighting key sustainability indicators, process mapping by flowcharting provides a structured comparison of how each SC functions and where 3D printing could enhance sustainability.

3.2 Comparative analysis framework

The comparative analysis evaluates traditional and 3D-printed SCs across three key sustainability dimensions: environmental, social, and economic. Each dimension is assessed based on specific criteria:

Environmental Sustainability

- **Carbon emissions:** Quantified based on energy consumption and transportation distances.
- **Water and energy use:** Measured using existing research on aquaculture and 3D printing (Ziegler et al., 2024; Home - Revo Foods, n.d.).
- **Waste generation:** Evaluated by comparing food loss and byproduct utilization in both SCs.

Social Sustainability

- **Labor impact:** Evaluated by examining shifts in employment dynamics between aquaculture and 3D printing-based production.
- **Consumer acceptance:** Established by investigating perceptions of 3D-printed seafood regarding taste, quality, and ethical considerations.
- **Ethical concerns:** Addressed by exploring issues such as overfishing, antibiotic use, and reliance on wild fish stocks.

Economic Sustainability

- **Production costs:** Measured by comparing cost per kilogram for traditional versus 3D-printed salmon.
- **Scalability potential:** Quantified by analyzing whether 3D printing can achieve large-scale market penetration.
- **Market dynamics:** Established by assessing consumer demand trends and regulatory challenges for alternative seafood production.

This framework ensures a holistic sustainability assessment, providing actionable insights into the strengths and limitations of each SC model.

3.3 Data collection and sources

The study relies on secondary data from:

- Peer-reviewed journal articles on salmon aquaculture, SC sustainability, and 3D food printing.
- Industry reports detailing carbon emissions, water consumption, and market trends for traditional and 3D-printed salmon.
- Case studies on Norwegian salmon farming and emerging 3D-printed food technologies.

To ensure data reliability and validity, findings were cross-referenced across multiple sources and aligned with existing sustainability benchmarks.

3.4 Analytical approach

A systematic comparison of the process mapping by flowcharting was conducted to identify strengths and weaknesses in both SC models. The analysis contextualizes findings within the broader sustainability discourse, assessing how 3D printing could serve as either:

1. A complementary innovation that improves sustainability within existing SCs.
2. A disruptive alternative capable of replacing traditional SC structures.

This methodological approach ensures a rigorous evaluation of the sustainability potential of 3D-printed seafood SCs, offering critical insights into their feasibility, challenges, and long-term viability.

4. FINDINGS

The comparative analysis of traditional and 3D-printed salmon SCs reveals significant differences across environmental, social, and economic dimensions. Findings from process mapping by flowcharting (Figures 1 and 2) illustrate the distinct structures and sustainability implications of each SC.

4.1 Traditional salmon SC

The traditional salmon SC is well-established, providing high-quality products to global markets. However, its resource intensity and environmental footprint present sustainability challenges (Figure 1).

Environmental Sustainability

The traditional SC is highly resource-intensive, requiring substantial freshwater inputs, marine-based feed, and significant energy consumption across farming, processing, and distribution stages. Cold chain logistics, particularly air freight, contribute significantly to its carbon footprint, with emissions ranging from 5 to 28 kg CO₂e per kilogram of salmon (Ziegler et al., 2024). While regulatory frameworks aim to mitigate environmental harm, persistent challenges include water pollution, waste accumulation, and ecosystem disruption from aquaculture practices.

Social Sustainability

Traditional SCs support employment across multiple sectors, including aquaculture, processing, and global logistics. However, ethical concerns remain, particularly regarding overcrowding in fish farms, antibiotic overuse, and dependence on wild-caught fish for feed. Additionally, cold chain infrastructure is not equally accessible worldwide, creating disparities in seafood availability and raising concerns about global food security and equitability.

Economic Sustainability

The traditional SC benefits from large-scale production capacity and strong consumer trust, making it a dominant force in the seafood market. However, long production cycles (2–3 years) and high capital investments in aquaculture facilities, feed production, and cold storage contribute to financial and operational constraints. These limitations reduce flexibility in responding to market fluctuations and add significant cost burdens to the SC.

4.2 3D-printed salmon SC

The 3D-printed salmon SC eliminates several resource-intensive stages present in traditional aquaculture, offering a simplified and localized production model (Figure 2).

Environmental Sustainability

The 3D-printed salmon SC significantly reduces the environmental footprint by eliminating aquaculture and minimizing reliance on long-distance cold storage. Carbon emissions are reduced by up to 86%, and freshwater consumption decreases by 95% compared to traditional methods (Home - Revo Foods, n.d.). Additionally, using plant-

based proteins and repurposing underutilized byproducts lowers pressure on marine ecosystems while enhancing resource circularity.

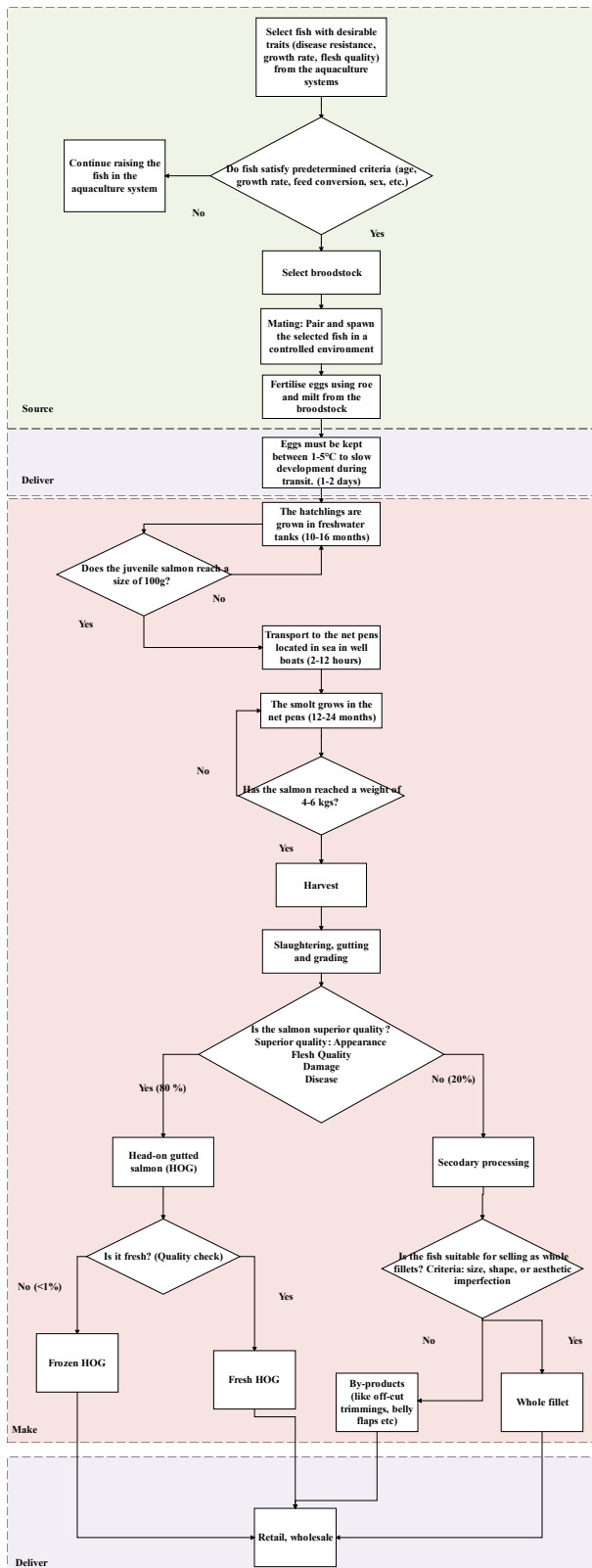


Figure 1. Traditional salmon SC (De et al., 2022; Marvin et al., 2020; Vempiliyath et al., 2021)

Social Sustainability

By removing the need for live animal farming, the 3D-printed SC addresses key ethical concerns related to overfishing, antibiotic use, and ecosystem disruption. The growing demand for sustainable and plant-based alternatives suggests strong market potential; however, consumer skepticism regarding taste, texture, and authenticity remains a challenge. Additionally, regulatory uncertainties surrounding food safety, labeling, and market approval may slow widespread adoption.

Economic Sustainability

The 3D-printed SC introduces a localized and scalable production model, reducing reliance on complex global logistics and cold chain networks. Current production capacities exceed 450,000 fillets per month, with an expected increase to 600,000 by Q3 2024, demonstrating its potential for large-scale market entry. While 3D printing can lower logistics and production costs, achieving cost parity with conventional aquaculture remains a key challenge, as further advancements in technology and market acceptance are required.

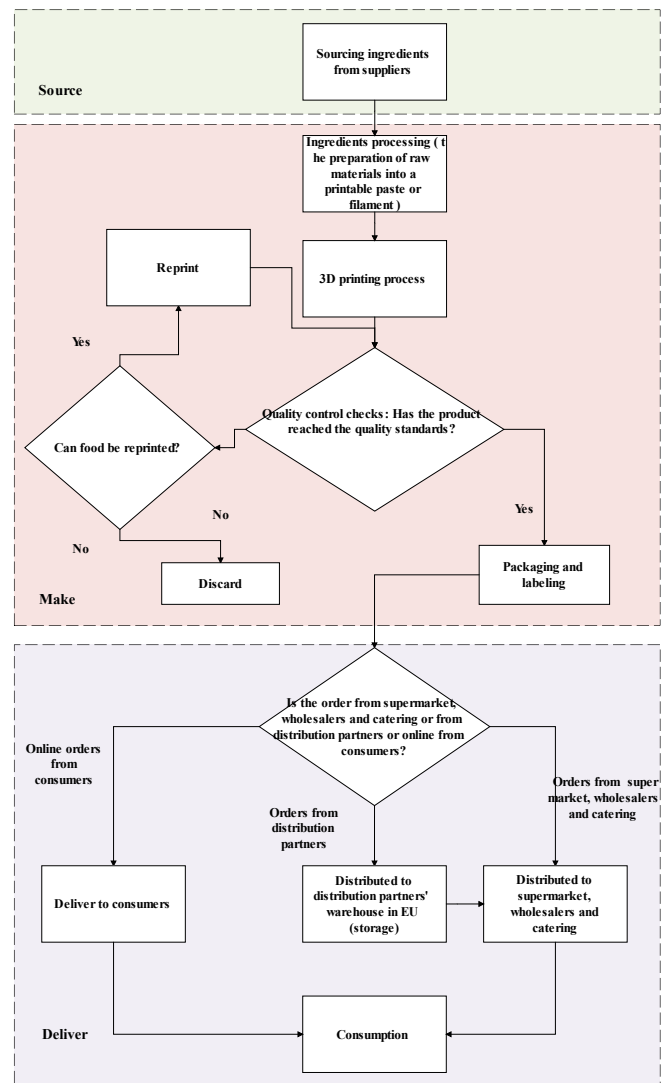


Figure 2. 3D-printed salmon SC (Home - Revo Foods, n.d.)

4.3 Comparative insights

A comparative summary of the traditional and 3D-printed salmon SCs (Table 1) highlights key trade-offs:

Environmental Impact: The 3D-printed salmon SC significantly reduces its environmental footprint compared to the traditional SC. By eliminating aquaculture and minimizing transportation, it lowers carbon emissions by up to 86% and freshwater consumption by 95% (Home - Revo Foods, n.d.). In contrast, the traditional SC remains highly resource-intensive, relying on marine-based feed, cold chain logistics, and long-distance transportation, all of which contribute to higher emissions and ecological pressures. While advancements in sustainable aquaculture practices have helped mitigate some of these effects, challenges such as waste management and water pollution persist.

Consumer Perception: Traditional SCs benefit from established consumer trust and market preference for natural seafood products. However, ethical concerns regarding overfishing, antibiotic use, and reliance on wild fish stocks for feed are driving interest in alternative protein sources. The 3D-printed SC aligns with this shift by providing a sustainable and ethical alternative, eliminating the need for live animal farming. Despite these advantages, consumer skepticism regarding taste, texture, and the perceived artificiality of 3D-printed seafood remains a barrier to widespread adoption.

Economic Feasibility: While traditional SCs have the advantage of large-scale production capacity and well-developed infrastructure, they incur higher costs due to long farming cycles, feed production, and complex logistics. The 3D-printed SC presents cost advantages in logistics and production speed, as decentralized manufacturing reduces reliance on expensive cold chain infrastructure. While current production capabilities show a potential for market expansion, achieving cost parity is critical to its sustainability.

Table 1. Traditional vs 3D-printed salmon SC

		Traditional salmon supply chain	3D printed salmon supply chain
Environmental sustainability	Decreased carbon emissions		✓
	Decreased energy consumption		✓
	Water and land usage reduction		✓
	Alternative ingredient		✓
Social sustainability	Food security		✓
	Personalization		✓
	High protein	✓	
	Increased freshness		✓
	Market reach	✓	
	Consumer acceptance	✓	
Economic sustainability	Job replacement		✓
	Reduced inventory		✓
	Extended shelf life		✓
	Waste reduction		✓
	Reduced intermediaries		✓
	Lead time reduction		✓
	Quick innovation		✓
	Cost efficiency	✓	
	Mass production	✓	

5. DISCUSSION

This study highlights the potential of 3D printing technology to address the sustainability challenges inherent in traditional salmon SCs. By comparing process models and sustainability

metrics, the findings reveal the transformative advantages of 3D-printed salmon, particularly in reducing environmental impact and enhancing operational efficiency. However, both SC models present unique strengths and challenges that warrant further exploration.

5.1 Environmental Impacts

The 3D-printed salmon SC offers substantial environmental benefits, including lower carbon emissions, freshwater use, and overall resource consumption. By eliminating aquaculture and long-distance cold storage, 3D printing reduces ecological strain and supports more sustainable production models. These findings align with existing research on additive manufacturing's potential to simplify SCs and reduce waste generation (Jia et al., 2016).

In contrast, the traditional SC remains resource-intensive, relying on marine-based feed, extensive water use, and high-energy logistics. While Norway's regulatory frameworks enforce sustainability standards, the industry still struggles with airfreight emissions, overfishing concerns, and ecosystem degradation. These limitations highlight the need for technological innovation to complement existing aquaculture systems.

5.2 Economic and Operational Efficiency

From an economic perspective, 3D printing introduces a more flexible, localized production model with faster turnaround times than traditional aquaculture. By reducing reliance on global logistics and cold chain networks, it offers opportunities for cost savings and streamlined SCs. However, challenges remain, particularly in achieving cost parity with conventional farming and scaling production to meet market demand.

In contrast, the traditional SC benefits from established infrastructure, market presence, and consumer trust. Norway's salmon industry is globally recognized for high-quality production, contributing to its economic resilience. However, long production cycles (2–3 years) and high operational costs limit its ability to adapt quickly to shifting market conditions. While 3D printing presents clear operational advantages, its long-term viability depends on overcoming technological and regulatory barriers.

5.3 Social and Ethical Considerations

The 3D-printed SC aligns with ethical food production trends by eliminating reliance on live animal farming and marine-based feed sources. This innovation addresses consumer concerns about overfishing, antibiotic use, and ecosystem degradation. However, widespread adoption depends on overcoming skepticism regarding the sensory qualities and authenticity of 3D-printed seafood. While consumer demand for sustainable alternatives is growing, further education and market positioning are needed to shift perceptions.

Conversely, the traditional SC benefits from strong consumer preference for naturally sourced seafood but faces increasing scrutiny over sustainability concerns. Ethical considerations related to fish welfare, feed sustainability, and pollution highlight the pressing need for industry improvements. This underscores the role of 3D printing as a complementary solution rather than a full replacement for traditional SCs.

5.4 Limitations and Future Research

While this study underscores the sustainability potential of 3D printing, several limitations remain. The analysis relies on secondary data, which may not fully capture the scalability and real-world feasibility of 3D-printed salmon production. Additionally, regulatory challenges and consumer behavior must be better understood to evaluate the technology's market potential. Future research should focus on:

- **Scalability and Long-Term Viability:** Exploring the operational limits of 3D-printed food production and its economic impact on traditional seafood markets.
- **Consumer Acceptance:** Conducting empirical studies to understand consumer perceptions, preferences, and willingness to adopt 3D-printed foods.
- **Regulatory Frameworks:** Examining policies and standards required to ensure food safety and foster innovation in the alternative protein sector.

6. CONCLUSIONS

This study compares traditional and 3D-printed salmon SCs, highlighting 3D printing's potential to enhance sustainability in seafood production. The findings show that 3D-printed salmon reduces carbon emissions by eliminating farming, long-distance transportation, and feed-intensive processes. Economically, 3D printing introduces a scalable, localized model, reducing reliance on cold chain logistics, though achieving cost parity with traditional aquaculture remains a challenge. While traditional SCs benefit from established infrastructure and consumer trust, their high resource consumption and operational costs highlight the need for sustainable alternatives. Socially, 3D printing addresses ethical concerns such as overfishing and antibiotic use, but consumer skepticism regarding taste, texture, and authenticity may limit widespread adoption. Rather than fully replacing traditional aquaculture, 3D printing can serve as a complementary solution, creating new market opportunities while improving environmental performance and long-term sustainability in seafood production.

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