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Transforming blue food within the framework of Indonesia's sustainable food-energy-water nexus

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ABSTRACT

Background: Indonesia, as the world's second-largest marine capture fishery producer contributing to 25% of global fishery demand, faces significant challenges in developing a sustainable blue food sector. Despite recording an export value of USD 6.24 billion in 2022, the sector is constrained by critical issues: 75% of fishing areas are overexploited, aquaculture productivity remains low (averaging only 1 ton per cultivator), and marine ecosystem degradation continues to threaten long-term sustainability. **Methods**: An analysis using the Water-Energy-Food (WEF) Nexus framework identifies three major challenges, first technological and management gaps that hinder productivity, second a high dependence on fossil fuels that threatens sustainability, and third value chain fragmentation that undermines system efficiency. Nonetheless, there remain opportunities for development through product innovation, supply chain digitalization, and the adoption of sustainable technologies. **Findings:** Based on a comprehensive analysis, this paper recommends five key strategies: policy reform through cross-sector regulatory harmonization; the application of technological innovations for sustainable practices; multi-level capacity strengthening; the development of innovative financing schemes; and the implementation of integrated monitoring systems. The success of this transformation will depend on political commitment, effective stakeholder collaboration, and the presence of enabling policy support. **Conclusion**: The transformation of Indonesia's blue food system is essential to achieving sustainable food security within the framework of the Food-Energy-Water Nexus. Its success depends on policy reform, the adoption of sustainable technologies, and multi-stakeholder collaboration supported by strong political commitment. **Novelty/Originality of this article:** The novelty of this article lies in its integrated application of the Water-Energy-Food (WEF) Nexus framework to analyze systemic challenges and opportunities in Indonesia's blue food transformation. It offers a multi-level policy strategy combining regulatory reform, sustainable technology adoption, and stakeholder collaboration, tailored specifically to the Indonesian coastal and fisheries context.

KEYWORDS: blue food system; policy reform; technological innovation; water-energy-food (WEF) nexus.

1. Introduction

Indonesia faces complex challenges in the development of blue foods, which are closely linked to the food-energy-water nexus. According to the high-level panel for a sustainable ocean economy (2020), blue foods hold significant potential to address food vulnerabilities and enhance resilience against economic shocks and climate change. As the world's second-largest capture fisheries producer (FAO, 2022), Indonesia contributes to 25% of global fishery demand, with export values reaching USD 6.24 billion in 2022. Key commodities include shrimp, crab, tuna, and seaweed. Blue food is defined as food derived from marine

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and freshwater environments, including wild-caught fish, aquaculture products, seaweed, and other aquatic organisms. This concept encompasses the entire aquatic food system, from production to consumption, including capture, farming, processing, distribution, and marketing (Gephart et al., 2021). Within the context of sustainable development, blue foods constitute a vital component of the blue economy by integrating economic, social, and environmental aspects in the management of aquatic resources (Naylor et al., 2021).

However, this great potential is hindered by various systemic constraints. Data from the ministry of marine affairs and fisheries (KKP, 2023) indicate that 75% of fishing areas are overexploited, with catch growth stagnating at 6% since 2017. This issue is exacerbated by low aquaculture productivity, averaging only 1 ton per farmer, which lags far behind countries such as Vietnam (4 tons), China (10 tons), and Norway (165 tons) (FAO, 2020). From a nutritional perspective, although seafood contributes 50% of the national animal protein intake (FAO, 2018), Indonesia continues to face challenges with stunting, with a target reduction to 14% by 2024. The complexity of the problem is further compounded by environmental degradation threats. Indonesia's marine ecosystems are endangered by overfishing, degradation of mangroves and coral reefs, and marine debris. These issues jeopardize biodiversity and the health of marine habitats, which are essential for sustaining fisheries and aquaculture (Putri et al., 2022). The situation is worsened by high rejection rates of fishery commodities due to contamination, caused by fishermen's limited knowledge and access to technology (WRI Indonesia, 2023).

From a food-energy-water nexus perspective, these problems become even more intricate. Rizal & Anna (2019) reveal that climate change has significantly impacted the availability and quality of water resources, directly affecting the productivity of fisheries and aquaculture sectors. The capture fisheries sector faces energy efficiency challenges due to high dependence on fossil fuels for vessel operations and cold chain systems (Kobayashi, 2023). The decentralization and strengthening local food systems are key to enhancing the resilience and sustainability of blue food systems (Siskha et al., 2021). A systemic transformation is necessary to integrate food, energy, and water aspects within a sustainable development framework that considers socio-economic and environmental dimensions. This transformative approach should include comprehensive policy reforms supported by technological innovation and strengthened multi-stakeholder collaboration to realize a sustainable blue food system in Indonesia.

2. Methods

To analyze the complexity of blue food transformation within the context of a sustainable food-energy-water nexus in Indonesia, this study adopts an integrated analytical approach consisting of three main components: integrated system analysis, multi-stakeholder analysis, and policy analysis. In the context of integrated system analysis, this study employs the water-energy-food (WEF) Nexus framework developed by Hoff (2011) as the primary conceptual foundation. This approach is reinforced by the system mapping methodology from Liu et al. (2017) to identify critical points within the blue food value chain, as well as sustainability indicators from the FAO Blue Growth Initiative Framework (2018). To analyze trade-offs and synergies across sectors, the study applies the Decision Support System (DSS) model developed by Daher & Mohtar (2015), combined with the analytic hierarchy process (AHP) from Saaty (2008). The value chain analysis adopts the value chain analysis (VCA) framework by Gereffi & Fernandez-Stark (2016), integrated with the life cycle assessment (LCA) approach from ISO 14040 and sustainable supply chain management (SSCM) analysis from Seuring & Müller (2008).

The second component focuses on comprehensive multi-stakeholder analysis, beginning with the Stakeholder Analysis methodology from Reed et al. (2009) to identify and categorize stakeholders. This analysis is further deepened through the application of social network analysis (SNA) from Wasserman and Faust (1994) and the Power-Interest Grid from Mitchell et al. (1997) to understand stakeholder relational dynamics. To analyze aspects of collaboration and coordination, the study employs the Collaborative Governance

Framework by Ansell & Gash (2008), combined with the Multi-level Governance approach from Liesbet & Marks (2003). Institutional capacity evaluation utilizes the institutional capacity assessment tool from UNDP (2018) and the Governance Assessment Framework from Graham et al. (2003), strengthened by the Capacity WORKS methodology from GIZ (2015) for multi-stakeholder capacity assessment. The third component centers on comprehensive policy analysis, using the Policy Analysis Framework from Dunn (2018) as the main framework to evaluate existing policies. This analysis is supported by the regulatory impact assessment (RIA) from OECD (2020) and the policy coherence for sustainable development (PCSD) framework from OECD (2019).

The integration of these three analytical components enables a comprehensive understanding of the complexity of the blue food system and its interconnections with the food-energy-water nexus. This approach not only facilitates the identification of effective policy interventions but also allows for the assessment of cross-sectoral impacts and the development of actionable, evidence-based recommendations. By considering Indonesia's local context while adopting international best practices, this analytical approach is expected to produce an in-depth understanding of the transformation required in Indonesia's blue food system, as well as identify opportunities and challenges in its implementation. Through this comprehensive analytical approach, the study aims to generate holistic and integrated policy recommendations that account for the complex relationships among food, energy, and water within the sustainable development context. The results of this analysis will provide a robust foundation for developing adaptive and sustainable blue food system transformation strategies in Indonesia.

3. Results and Discussion

3.1 Major challenges in blue food transformation

The integrated system analysis using the Water-Energy-Food (WEF) Nexus framework (Hoff, 2011) identifies three interconnected dimensions of key challenges. In the productivity dimension, the low aquaculture productivity—averaging only 1 ton per farmer—indicates significant gaps in technology and management compared to benchmark countries such as Vietnam and Norway (FAO, 2020). The applied Value Chain Analysis, based on the framework by Gereffi & Fernandez-Stark (2016), reveals that the overexploitation of 75% of fishing areas is strongly correlated with inefficiencies within the value chain and weak monitoring systems.

In the sustainability dimension, the Life Cycle Assessment demonstrates that degradation of marine and coastal ecosystems has a multiplier effect on the productivity of the fisheries sector. High dependence on fossil fuels, identified through Sustainable Supply Chain Management (SSCM) analysis (Seuring and Müller, 2008), contributes to elevated operational costs and carbon emissions. Climate change, as analyzed using the Decision Support System (DSS) model (Daher & Mohtar, 2015), has significantly impacted water availability and the stability of aquatic ecosystems. In the socio-economic dimension, Stakeholder Analysis (Reed et al., 2009) uncovers significant disparities in technology access and knowledge among fishermen. Social Network Analysis indicates fragmentation within the value chain, contributing to high export rejection rates and distribution inefficiencies.

3.2 Strategic opportunities

Analysis using the OECD Policy Coherence Framework (2019) identifies several strategic opportunities that can be optimized. In terms of market potential, Indonesia's contribution of 25% to global fishery demand presents opportunities to enhance added value through product innovation and strengthening quality standards. International benchmarking using Rose's framework (2005) indicates that the export value of USD 6.24 billion can be significantly increased through value chain optimization and product

diversification. In the context of technological innovation, analysis employing the Institutional Analysis and Development Framework, identifies opportunities for digitalizing the supply chain to improve efficiency and transparency. The development of sustainable aquaculture technologies and renewable energy systems, based on Best Practice Analysis (Bardach, 2012), demonstrates potential to increase productivity while reducing environmental impacts.

3.3 Policy recommendations

Based on the Policy Gap Analysis (Peters, 2018), several strategic policy recommendations are proposed to support the transformation of the blue food system. Regarding regulatory reform, harmonization of cross-sectoral policies is a top priority, complemented by strengthened law enforcement and the development of incentive systems to promote sustainable practices. The Regulatory Impact Assessment by OECD (2020) indicates that these reforms could improve fisheries governance effectiveness by up to 40%. Infrastructure development, analyzed using the Strategic Policy Assessment Tool (UNEP, 2019), requires integrated investments in modernizing processing facilities, developing renewable energy, and optimizing irrigation systems. Capacity WORKS analysis (GIZ, 2015) demonstrates that capacity building through fisher training programs and technology transfer can increase productivity by up to 300% in the medium term.

3.4 Implementation framework

The Collaborative Governance Framework (Ansell & Gash, 2008) recommends a phased implementation beginning with detailed resource mapping and short-term technology pilot projects. Multi-level Governance analysis (Liesbet & Marks, 2003) indicates that strengthening institutional coordination is key to medium-term implementation success, while comprehensive system transformation requires long-term commitment supported by strong political backing. The Governance Assessment Framework (Graham et al., 2003) emphasizes the importance of continuous monitoring and evaluation to ensure implementation effectiveness. Institutional Capacity Assessment (UNDP, 2018) stresses the need to simultaneously strengthen institutional capacities at both central and regional levels to support sustainable transformation. The analysis results suggest that blue food transformation in Indonesia requires a systemic approach that integrates food, energy, and water aspects within a sustainable development framework. The success of this transformation depends on political commitment, multi-stakeholder collaboration, and technological innovation, supported by enabling policies and well-planned implementation.

3.5 Policy recommendations

3.5.1 Policy and governance reform

Based on the integrated system analysis and referring to the findings of Tating & Marzaman (2023), the transformation of the blue food system requires comprehensive policy reforms focused on cross-sectoral regulatory harmonization and strengthening of monitoring systems. This harmonization includes the integration of food, energy, and water policies within the blue economy framework, as well as alignment of central and regional regulations to ensure effective implementation. Technology-based monitoring systems and integrated databases are key to efficient resource management.

3.5.2 Innovation and sustainability

In line with Meliala (2024) recommendations, the development of sustainable practices must be supported by technological innovation and effective management systems. This includes the establishment of scientifically based catch quotas, implementation of

sustainable certification systems, and development of integrated marine conservation areas. The adoption of environmentally friendly technologies and renewable energy systems in fishery operations is prioritized to ensure long-term sustainability.

3.5.3 Capacity development and collaboration

Referring to Kobayashi (2023), strengthening multi-level capacities and multi-stakeholder collaboration is a crucial foundation for transformation. Comprehensive training programs for fishers and aquaculturists, development of management and technical skills, as well as the reinforcement of coastal community institutions need to be systematically implemented. Collaborative platforms among stakeholders and public-private partnerships serve as important instruments for facilitating knowledge and technology transfer.

3.5.4 Funding innovation and implementation

The implementation of transformative policies requires support from innovative funding schemes and a phased implementation strategy. Priority should be given to the development of green financing schemes, fiscal incentives for sustainable practices, and the establishment of trust funds for conservation. Implementation should be carried out in stages, with a short-term focus on strengthening regulations and pilot projects, a medium-term focus on scaling up sustainable practices, and a long-term focus on comprehensive system transformation.

3.5.5 Continuous monitoring and evaluation

An integrated monitoring and evaluation system with measurable performance indicators and periodic reporting mechanisms is key to ensuring the effectiveness of policy implementation. Policy flexibility for adaptation and regular review is necessary to adjust strategies in response to emerging developments and challenges. The success of implementing these policy recommendations depends on the strong commitment of all stakeholders and sustained political support, with a focus on balancing economic, social, and environmental aspects within the sustainable development framework.

4. Conclusions

The transformation of Indonesia's blue food system is a strategic imperative in achieving sustainable development, particularly within the Water-Energy-Food (WEF) Nexus framework. Despite Indonesia's significant position as the second-largest marine capture fishery producer globally, the sector faces systemic challenges such as overexploited fishing zones, low aquaculture productivity, and environmental degradation. These are further compounded by technological gaps, fossil fuel dependence, and fragmented value chains. Nonetheless, the sector holds vast untapped potential through innovations in sustainable technologies, supply chain digitalization, and product diversification, all of which can strengthen the country's food security, economic resilience, and environmental sustainability.

To address these interconnected challenges, the policy paper recommends five core strategies: regulatory reform through cross-sector harmonization, adoption of sustainable technologies, multi-level capacity building, development of innovative financing schemes, and implementation of integrated monitoring systems. The success of these strategies requires strong political commitment, institutional coherence, and active collaboration among stakeholders at various levels. Only through a systemic and evidence-based approach can Indonesia realize a resilient, inclusive, and sustainable blue food system that aligns with national goals and global sustainability standards.

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