An Integrated Conceptual Framework for the Use of Duckweed in Domestic Aquaculture: Socioeconomic and Spatial Perspectives in Malaysia

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ABSTRACT

The rising demand for commercial fish feed has created significant economic pressure on aquaculture farmers, particularly small-scale operators with limited financial resources. In Malaysia, this challenge affects the sustainability and profitability of domestic aquaculture systems. Although duckweed (*Lemna* spp.) has been widely recognized as a high-protein and cost-effective alternative feed source, studies examining its socioeconomic and spatial implications remain limited. This paper develops an integrated conceptual framework by combining the Sustainable Livelihood Approach (SLA), Sustainable Aquaculture Framework (SAF), and Circular Economy Model (CEM). The framework explains how duckweed utilization may reduce feed costs, improve production efficiency, strengthen farmer well-being, and support environmental sustainability across different spatial settings. The proposed framework contributes to the literature by offering a multidisciplinary perspective and provides a foundation for future empirical research and policy interventions aimed at developing a more inclusive and resilient domestic aquaculture sector in Malaysia.

Keywords: duckweed; domestic aquaculture; sustainability; livelihood resilience; spatial factors; Malaysia

INTRODUCTION

The aquaculture sector plays a strategic role in securing global protein supplies, especially in the face of increasing world population and pressure on capture fisheries resources (Nabi et al., 2025). However, the sustainability of this sector is increasingly challenged by rising input costs, especially commercial fish feed which contributes the largest percentage to the operating cost structure. In the context of a developing country such as Malaysia, this pressure is felt more by small-scale and domestic farmers who operate with limited financial and technical resources (Tan et al., 2024).

In Malaysia, domestic aquaculture not only functions as a secondary economic activity, but also as a strategy to support household food security (Ghazali & Kadir, 2025). However, the high reliance on commercial fish feed based on imported ingredients such as fishmeal and soy has increased the vulnerability of small-scale farmers to global price fluctuations, thus affecting their profit margins and the viability of their operations (Obi et al., 2025).

In this regard, attention has been shifted to the use of alternative food sources that are more sustainable, cheap and easily available. One potential source is duckweed (Lemna spp.), a floating aquatic plant with a fast growth rate and high protein content (Song et al., 2025; Takács et al., 2025; Devlamynck et al., 2021). Previous studies have shown that duckweed has the potential to be used as a partial replacement ingredient in fish feed formulations without affecting livestock growth rates (Herawati et al., 2020; Fiordelmondo et al., 2022). In addition, its ability to absorb excess nutrients in water makes it an important component in improving the ecological efficiency of aquaculture systems (Paolacci et al., 2021; Rifai et al., 2024).

However, most studies on duckweed have focused on technical and nutritional aspects in controlled environments, while the socioeconomic dimensions, community acceptance and spatial variation in the actual context of domestic farming is still not emphasized (Song et al., 2025; Takács et al., 2025). Understanding of the feasibility of duckweed adoption at the community level remains limited, particularly in the Malaysian context, which is characterised by diverse socioeconomic and environmental conditions (Song et al., 2025; Takács et al., 2025).

Therefore, this paper urges that the use of duckweed should not be seen solely as a technical innovation but should be understood as an integrated strategy involving the interaction of economic, social, environmental and spatial factors (Ahmed et al., 2008; Apine et al., 2019). By integrating the Sustainable Livelihood Approach (SLA), Sustainable Aquaculture Framework (SAF) and Circular Economy Model (CEM), this paper proposes a conceptual framework to explain the role of duckweed in improving the cost efficiency, economic resilience and sustainability of domestic aquaculture systems (Paolacci et al., 2021; Paolacci et al., 2022; Osei et al., 2025; Daga et al., 2025). This framework also considers the role of duckweed as an ecological and economic component in aquaculture systems, in line with previous evidence on its nutritional potential, growth efficiency and applications in water treatment and resource recycling (Song et al., 2025; Sosa et al., 2024; Sońta et al., 2019). It is hoped that this framework can serve as a basis for empirical research and support policy development that is more responsive to the needs of smallholder farming communities in Malaysia.

DOMESTIC AQUACULTURE AND THE COST STRUCTURE CHALLENGES

Domestic aquaculture often functions as a household economic strategy, particularly among low- and middle-income communities that rely on multiple sources of income to ensure survival. In many cases, this activity is not seen as a full-time commercial enterprise, but rather as a mechanism to support existing incomes and as a household food security strategy. This role is in line with findings in studies of small-scale fisheries development that show how aquaculture is part of a community's livelihood strategy, especially when analyzed through the Sustainable Livelihoods Framework approach, which emphasizes the interaction between assets, strategies and livelihood outcomes (Ahmed et al., 2008; Apine et al., 2019). Through this perspective, domestic aquaculture is not just an economic activity, but also a form of adaptation to economic pressures and resource uncertainty in the local context.

In contrast to large-scale commercial operations that have access to capital, technology and a wider market network, domestic aquaculture is usually carried out on a small-scale basis with limited resources and relies on family labor. This small scale of operation means that domestic farmers are more likely to adopt low-intensity production systems, with minimal input use and low levels of mechanisation. In this context, the cost structure plays a critical role in determining the feasibility and sustainability of the activity, as any increase in input costs will directly impact the net profit earned. Previous studies have shown that small-scale farmers have a limited capacity to absorb cost increases, making them more vulnerable to economic pressures than large-scale operators (Ahmed et al., 2008). This situation suggests that cost sensitivity is a key feature that distinguishes domestic aquaculture from commercial systems.

The cost of fish feed has been identified as the main component that burdens small-scale farmers the most, and in many cases, it is a determining factor for the sustainability of farming operation. The dependence on commercial feeds based on imported materials such as fishmeal and soy leaves farmers exposed to global price fluctuations, including changes in the supply chain and production costs of raw materials. This creates instability in the cost structure, which in turn affects the financial planning of small-scale farmers. A study by Sońta et al. (2019) shows that small-scale aquaculture systems are very sensitive to changes in input costs, where a small increase in the price of fish feed can significantly reduce profit margins. In certain situations, these increases in costs can also cause farmers to reduce feeding rates, which ultimately affects fish growth rates and overall production yields.

Other than that, farmers also face a variety of multidimensional risks, encompassing environmental, economic and social aspects. Environmental risks such as inconsistent water quality, pollution and climate change can affect fish health and survival rates. At the same time, social risks such as lack of technical knowledge, limited access to training and lack of institutional support also limit farmers' ability to adopt more efficient management practices. This is in line with the findings of studies on small-scale fishing community livelihood strategies which highlight that households in this sector often operate under conditions that are exposed to both economic and ecological pressures (Apine et al., 2019). This situation makes domestic aquaculture a potential activity, but at the same time a high-risk one if not supported by appropriate management strategies.

In this regard, there is a clear need to restructure the input management approach in domestic aquaculture, particularly using more sustainable, affordable and locally based alternative sources. This approach can not only reduce dependence on imported inputs but also has the potential to increase the efficiency of resource use in the production system. In this context, the use of duckweed as an alternative fish feed source is seen as a potential option, given that this plant has a high protein content and the ability to grow rapidly in a variety of aquatic environments. In addition, duckweed also plays an important role in increasing the ecological efficiency of aquaculture systems by absorbing excess nutrients in the water, thus supporting a more sustainable and integrated approach (Paolacci et al., 2021; Paolacci et al., 2022; Rifai et al., 2024). Therefore, the integration of alternative sources such as duckweed is not only relevant from an economic perspective, but also important in strengthening the resilience of domestic aquaculture systems in the long term.

DUCKWEED AS AN INNOVATION IN AQUACULTURE SYSTEMS

Duckweed is a floating aquatic plant that has great potential as an alternative food source in aquaculture, especially in the context of small-scale production systems that require low-cost and easily accessible inputs. This plant is characterized by a very fast growth rate and the ability to reproduce vegetatively in nutrient-rich environments, making it an efficient source of biomass. From a nutritional point of view, duckweed has a high protein content and a balanced amino acid profile, making it comparable to conventional protein sources such as fishmeal and soy. This ability positions duckweed as a competitive alternative in fish feed formulations, especially in an effort to reduce dependence on imported raw materials that are unstable in terms of price and supply (Takács et al., 2025; Devlamynck et al., 2020; Habeeb et al., 2025). In this context, duckweed is not only seen as a substitute for livestock feed, but also as an innovation that has the potential to change the input structure in aquaculture systems.

Other than its nutritional value, duckweed's ability to absorb excess nutrients from water also makes it an important component in improving water quality and the ecological efficiency of aquaculture systems. In conventional aquaculture systems, the accumulation of nutrients such as nitrogen and phosphorus often causes eutrophication problems and disrupts the balance of aquatic ecosystems. Duckweed functions as a natural biofilter that is able to absorb these nutrients and convert them into biomass that can be reused as animal feed. This ability has been proven in integrated multitrophic system studies that evaluated the effectiveness of nutrient removal by Lemna spp. as well as biomass production in integrated water treatment systems (Paolacci et al., 2022; Paolacci et al., 2022b; Waluyo et al., 2024). Therefore, the use of duckweed not only increases production efficiency, but also contributes to more systematic waste management in aquaculture systems.

From an economic perspective, the use of duckweed has the potential to reduce feed costs, which are the largest component of the domestic aquaculture cost structure. By producing feed in-house using local resources, small-scale farmers can reduce their dependence on imported commercial feeds that are vulnerable to global market price fluctuations. In addition, the use of duckweed can also increase net profits by reducing input costs without compromising production performance. Studies have shown that the use of duckweed as an aquafeed not only supports competitive fish growth, but also improves muscle composition and fish health parameters, thus ensuring that the quality of farmed products remains guaranteed (Alkhamis, 2024; Song et al., 2026). In addition, duckweed functions as an economic innovation that can improve the cost efficiency and financial resilience of small-scale farmers.

From a sustainability perspective, duckweed supports a circular economy approach through nutrient reuse and waste reduction in the production system. In a linear economic model, nutrient waste from aquaculture activities is often released into the environment without being reused, thus contributing to pollution. In contrast, in a circular economy approach, these nutrients are recycled through duckweed cultivation which is then used as animal feed, creating a more efficient and sustainable resource cycle. This approach is particularly relevant in effluent integration systems, where nutrient-rich wastewater is used to produce economically valuable biomass

(Tavares et al., 2010; Paolacci et al., 2022). Therefore, duckweed not only contributes to cost reduction, but also plays an important role in reducing environmental impacts and improving the sustainability of the aquaculture system as a whole.

However, the effectiveness of duckweed use is not consistent and is highly dependent on environmental factors and the cultivation method used. Factors such as water quality, nutrient content, temperature and lighting affect the growth rate and nutritional content of duckweed. Variations in these factors can cause significant differences in nitrogen absorption capacity and biomass performance produced. Studies have shown that inconsistencies in environmental conditions can affect the effectiveness of duckweed as a source of livestock feed, thus affecting the level of acceptance among farmers (Devlamynck et al., 2020). Therefore, environmental management and selection of appropriate cultivation methods are important elements in ensuring duckweed use in domestic aquaculture systems.

Community acceptance also plays an important role in determining the success of this innovation. In the context of domestic aquaculture, the decision to adopt an innovation is often influenced by risk perception, previous experience and compatibility with long-standing traditional practices. Innovations such as the use of duckweed may be seen as risky if they are not in line with existing knowledge or are not supported by practical evidence in the local context. Studies have shown that small-scale farmers tend to be more cautious in adopting new technologies, especially when it involves changes in livestock feeding systems (Sońta et al., 2019). Therefore, the analysis of duckweed use in aquaculture systems needs to consider social and institutional dimensions, including the role of community networks, agency support and knowledge dissemination, to ensure that these innovations can be accepted and applied effectively.

ROLE OF SPATIAL FACTORS IN DOMESTIC AQUACULTURE

From a geographical perspective, duckweed use cannot be separated from the spatial and regional context because each location has different physical and socioeconomic characteristics that influence the implementation of an innovation. Variations in physical factors such as water resource availability, microclimate stability, lighting levels and suitability of the culture space play an important role in determining the growth rate and productivity of duckweed. At the same time, socioeconomic factors such as access to markets, supply networks, institutional support and the level of community knowledge also influence the feasibility of duckweed use in domestic aquaculture systems. The interaction between these physical and social factors shows that innovation does not occur in a vacuum but is instead influenced by the spatial configuration specific to a region (Devlamynck et al., 2020; Paolacci et al., 2022b). Therefore, a geographical approach provides a more comprehensive framework for understanding how spatial variation shapes the adoption and effectiveness of innovations in the aquaculture sector.

In urban areas, physical space constraints and land use pressures have led farmers to adopt more intensive and flexible small-scale aquaculture systems, such as the use of tanks, closed systems or integration with urban agriculture activities. Moreover, limited space requires more efficient use of input and more careful management to ensure that productivity can be maintained. Conversely, in peri-urban and rural areas, the availability of more space allows for the implementation of more diverse aquaculture systems, including open ponds and integrated systems involving more extensive water resource management. These differences not only influence management strategies and input choices but also determine the suitability of duckweed as an alternative food source. The effectiveness of duckweed is highly dependent on factors such as nutrient loading, light intensity and water quality, which usually vary according to location and type of environment (Waluyo et al., 2024; Alkhamis, 2024). Therefore, spatial variation results in differences in technical performance and the level of innovation success in domestic aquaculture systems.

Spatial dimensions also influence the level of innovation adoption among farming communities. Locations with better access to information resources, training and institutional support tend to show higher rates of innovation adoption than marginalized areas. In this context, factors such as geographical location, social networks and relationships with relevant agencies play an important role in shaping farmers' decisions to adopt duckweed use. Communities with exposure to technology and technical support are more likely to see innovation as an opportunity, while communities with less access may see it as a risk. This shows that innovation adoption depends not only on technical effectiveness, but also on the social and institutional context that varies by space (Sońta et al., 2019). Therefore, an approach that takes into account spatial variation is important to ensure that duckweed use can be adapted to local contexts and is not implemented uniformly without considering regional differences. Spatial analysis allows for a deeper understanding of how location factors influence farmers' economic decisions, including input selection, management strategies and the level of readiness to adopt innovations. In addition, this approach also helps identify areas with high potential for the implementation of duckweed-based innovations, as well as areas that require additional support in terms of training and capacity building. In addition, understanding spatial variation is not only important to increase the effectiveness of innovations, but also to ensure that planned interventions are more inclusive, responsive and in line with local realities in domestic aquaculture systems.

INTEGRATED CONCEPTUAL FRAMEWORK FOR THE USE OF DUCKWEED IN DOMESTIC AQUACULTURE

This paper proposes a conceptual framework that integrates three main theoretical approaches, namely the Sustainable Livelihood Approach (SLA), Sustainable Aquaculture Framework (SAF) and Circular Economy Model (CEM) to form a comprehensive analytical perspective on the use of duckweed in domestic aquaculture systems. The integration of these three approaches allows for a more comprehensive understanding of the interactions between social, economic and environmental dimensions in the context of smallholder farming communities, which often operate under resource-limited and high-risk conditions.

The SLA approach has been widely used to assess social factors, livelihood assets and the role of institutional support in small-scale fishing communities, emphasizing how households combine various strategies to achieve economic survival (Ahmed et al., 2008; Apine et al., 2019). In this context, the use of duckweed can be interpreted as a form of adaptive strategy that increases the ability of households to manage cost risks and income volatility. Meanwhile, SAF emphasizes the integration of biological, ecological and technical components in integrated aquaculture systems, including resource efficiency and waste management in production systems (Paolacci et al., 2022; Paolacci et al., 2022b). CEM emphasizes the principles of resource recycling, waste reduction and nutrient reuse, which make duckweed an important component in shaping more sustainable and efficient aquaculture systems (Osei et al., 2025; Daga et al., 2025). Therefore, the integration of these three approaches allows for an analysis that encompasses not only technical aspects, but also the livelihood and sustainability dimensions of the system.

In this framework, duckweed use is defined as a key variable that acts as a catalyst for change in domestic aquaculture systems. This use is expected to directly influence the cost structure, by reducing dependence on imported commercial feed, as well as increasing production efficiency by optimizing nutrient use in the system. This effect in turn has an impact on the well-being of farmers, including increased net income, economic stability and household food security. This relationship is supported by studies showing that duckweed has high nutritional value, potential as a low-cost aquafeed and has positive effects on fish growth and health (Song et al., 2026; Alkhamis, 2024; Takács et al., 2025). In addition, its ability to absorb excess nutrients and improve water quality also increases the efficiency of the overall aquaculture system, thus reducing dependence on additional inputs (Paolacci et al., 2022; Waluyo et al., 2024).

However, the relationship between duckweed uses and expected yields is not direct or uniform but is influenced by several intermediary and moderator variables. Environmental factors such as water quality, nutrient content, temperature and light intensity play an important role in determining the growth rate and effectiveness of duckweed as a feed source. Variations in these factors can cause differences in the performance of aquaculture systems, thus affecting the economic returns obtained by farmers. Studies have shown that duckweed performance is highly dependent on nutrient composition and local environmental conditions (Devlamynck et al., 2020). At the same time, social factors such as the level of knowledge, experience, community networks and institutional support also influence the level of acceptance and use of this innovation among small-scale farmers. Acceptance of innovations is often associated with perceptions of risks and benefits, which vary according to social background and individual experiences (Sońta et al., 2019).

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In addition, spatial factors play an important mediating variable in this framework, as spatial variations affect both the technical and social dimensions of duckweed use. Differences between urban, peri-urban and rural areas in terms of space availability, water resources, pollution levels, and access to markets and institutional support will determine the suitability and effectiveness of duckweed use. For example, urban areas may face space constraints but have better access to technology and markets, while rural areas have more space but may face constraints in terms of technical and infrastructure support. These variations affect the cultivation methods, space utilization, and effectiveness of duckweed-based water treatment technologies (Waluyo et al., 2024; Paolacci et al., 2022b). Therefore, spatial factors not only affect technical performance, but also shape the adoption patterns of innovations among communities.

Based on the integration of these factors, this framework argues that the use of duckweed in domestic aquaculture systems has the potential to produce a cascade effect, namely reduced operating costs, increased production efficiency and strengthened household economic resilience. At the same time, this use also contributes to environmental sustainability through waste reduction and optimization of nutrient use, in line with the principles of the circular economy. Duckweed serves as a bridge between the economic and ecological dimensions, where nutrient waste is converted into valuable resources that can be reused in the production system (Habeeb et al., 2025; Sosa et al., 2024). Therefore, this framework emphasizes that innovation in aquaculture cannot be assessed in isolation but needs to be understood as part of an interconnected system of economics, society and the environment.

Overall, this conceptual framework provides a more holistic analytical basis for assessing the role of duckweed as an innovation in domestic aquaculture. By integrating economic, social, environmental and spatial dimensions, this framework not only contributes to strengthening the existing literature but also broadens the discussion of domestic aquaculture from a technical perspective to an integrated approach that incorporates the dimensions of livelihood, sustainability and spatial variation. Figure 1 illustrates the relationships between key variables, mediating variables, moderator factors and spatial dimensions in the proposed conceptual framework.

Figure 1 illustrates the hypothesised relationships between duckweed utilisation as the independent variable, cost structure and production efficiency as mediating variables, environmental and social factors as moderating influences, and farmer well-being as the dependent outcome within different spatial contexts. Figure 1 presents the proposed conceptual framework in which duckweed utilisation influences farmer well-being indirectly through cost structure and production efficiency, while environmental, social, and spatial factors shape the strength and feasibility of adoption.

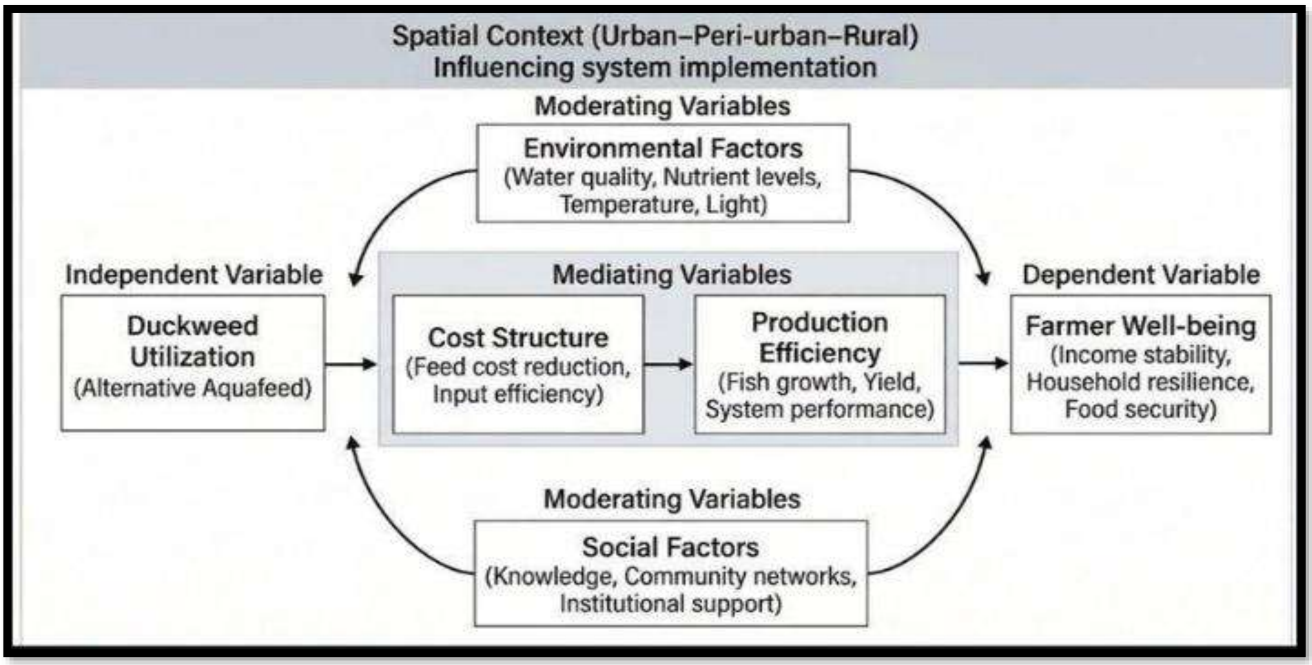

Figure 1: Conceptual Framework for the Use of Duckweed in Domestic Aquaculture Based on Socioeconomic and Spatial Dimensions in Malaysia

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Table 1 operationalises the proposed conceptual framework by translating each theoretical dimension into measurable variables, duckweed applications, and expected outcomes.

Table 1. Operationalisation of the Proposed Conceptual Framework

Framework Dimension	Core Variables	Duckweed Application in Domestic Aquaculture	Measurable Indicators	Expected Outcomes
Sustainable Livelihood Approach (SLA)	Household assets, skills, institutional support	Low-cost self-cultivated feed source for small farmers	Feed expenditure reduction, training participation, income diversification	Improved household resilience
Sustainable Aquaculture Framework (SAF)	Feed efficiency, water quality, fish growth	Use of duckweed as supplementary aquafeed and nutrient absorber	Fish growth rate, survival rate, water clarity, feed conversion ratio	Higher productivity and system efficiency
Circular Economy Model (CEM)	Waste reuse, nutrient recycling, biomass recovery	Duckweed grown using nutrient-rich wastewater and reused as feed	Biomass yield, reduced waste discharge, nutrient reuse rate	Environmental sustainability
Spatial Dimension	Urban/peri-urban/rural setting, market access, land availability	Suitability differs by location and available farming space	Distance to market, pond/tank area, water access	Context-specific adoption feasibility

Table 1 operationalises the proposed conceptual framework by translating the major theoretical dimensions into measurable variables, practical duckweed applications, and expected outcomes. The Sustainable Livelihood Approach highlights how duckweed utilisation may strengthen household resilience through feed cost reduction, income diversification, and improved access to low-cost farming inputs. This is particularly relevant for small-scale domestic aquaculture farmers operating under financial constraints.

The Sustainable Aquaculture Framework and Circular Economy Model further demonstrate the production and environmental benefits of duckweed adoption. Duckweed may function simultaneously as a supplementary aquafeed and nutrient absorber, thereby improving feed efficiency, water quality, and waste reuse. Meanwhile, the spatial dimension emphasises that adoption feasibility is not uniform, as implementation depends on land availability, market access, and farming conditions across urban, peri-urban, and rural settings. Therefore, the framework provides a basis for future empirical testing using context-specific indicators. Collectively, these interacting dimensions indicate that duckweed adoption may simultaneously improve livelihood resilience, production performance, and environmental sustainability within different spatial contexts.

RESEARCH IMPLICATIONS

Academically, this paper contributes to expanding the discourse on domestic aquaculture by presenting an integrated analysis encompassing socioeconomic, environmental, and spatial dimensions. This approach enriches the existing literature, which has largely focused on technical aspects such as fish growth performance, water treatment effectiveness, and feed formulation, while giving limited attention to how innovations such as duckweed function within the realities of smallholder livelihoods. By integrating the Sustainable Livelihood Approach, Sustainable Aquaculture Framework, and Circular Economy Model, this paper offers a more comprehensive conceptual foundation for understanding domestic aquaculture as a complex and interconnected livelihood system shaped by economic, social, and environmental factors.

In practical terms, the proposed framework provides strategic guidance for smallholder farmers in assessing the potential of duckweed as an alternative feed source. A clearer understanding of the relationships among cost structure, system efficiency, environmental conditions, and social capacity enables farmers to make more informed decisions in optimizing their aquaculture operations. In addition, the framework highlights important intervention areas, including technical training, improved cultivation methods, efficient nutrient management, and stronger community networks, all of which may enhance productivity and system resilience.

From a policy perspective, the findings provide a basis for more targeted and context-sensitive support programmes for smallholder communities. These may include training initiatives, incentives for integrated aquaculture systems, demonstration farms, and the promotion of cost-effective and sustainable alternative feed sources. By emphasizing spatial factors, this paper also highlights the need for differentiated strategies across urban, peri-urban, and rural areas according to local environmental conditions, resources, and community capacities. Such a location-sensitive approach could improve policy effectiveness and strengthen the long-term resilience of the domestic aquaculture sector.

CONCLUSION

Overall, this paper highlights that the use of duckweed in domestic aquaculture has significant strategic value from economic, social, and environmental perspectives. As a cost-effective, easily cultivated, and low-impact alternative feed source, duckweed offers a relevant option for smallholder farmers facing rising input costs and market uncertainty. However, the effectiveness of duckweed adoption depends not only on its biological characteristics, but also on the interaction of economic, social, environmental, and spatial factors.

Therefore, successful adoption requires an integrated approach that considers local conditions, livelihood strategies, and institutional capacity. The proposed conceptual framework provides a systematic basis for future empirical research and offers opportunities to test the relationships among the identified variables. Ultimately, strengthening domestic aquaculture requires not only technological improvements, but also social transformation, improved access to resources, and a deeper understanding of spatial realities. This can contribute to a more sustainable, inclusive, and resilient aquaculture sector in Malaysia.

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Declarations

9.1. Ethical considerations

This article does not contain any studies with human participants or animals performed by any of the authors. The ethical approval reference (USM/JEPeM/PP/23010099) pertains to the related research activities under the authors' institution.

9.2. Use of artificial intelligence (AI)

The authors declare that the generative artificial intelligence (AI) tool ChatGPT was used exclusively for grammatical improvement. The use of AI did not influence the scientific content, study design, data analysis, data interpretation, results, or conclusions of the manuscript. Full responsibility for the content remains with the authors.

9.3. Conflict of Interest

The authors declare no conflicts of interest

9.4. Funding

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REFERENCES

1. Ahmed, N., Allison, E. H., & Muir, J. F. (2008). Using the sustainable livelihoods framework to identify constraints and opportunities to the development of freshwater prawn farming in southwest Bangladesh. *Journal of the World Aquaculture Society*. https://doi.org/10.1111/j.1749-7345.2008.00198.x
2. Alkhamis, Y. A. (2024). Effect of aquaponically grown duckweed as a sustainable feed on growth indices, water quality, and digestive activities for the Nile tilapia reared in aquaponic culture. *Egyptian Journal of Aquatic Biology and Fisheries*. https://doi.org/10.21608/ejabf.2024.350076
3. Apine, E., Turner, L. M., Rodwell, L. D., & Bhatta, R. (2019). The application of the sustainable livelihood approach to small-scale fisheries: The case of mud crab Scylla serrata in southwest India. *Ocean and Coastal Management*. https://doi.org/10.1016/j.ocecoaman.2018.12.024
4. Daga, S., Yadav, K., Singh, P., & Mishra, V. (2025). Beyond the take-make-dispose model Unlocking the power of circular economy for an environmentally resilient future. *In Circular Economy and Environmental Resilience: Solutions for a Sustainable Tomorrow*, Volume 1. https://doi.org/10.1007/978-3-031-93091-1_1
5. Devlamynck, R., Fernandes de Souza, M., Bog, M., Leenknegt, J., Eeckhout, M., & others. (2020). Effect of the growth medium composition on nitrate accumulation in the novel protein crop Lemna minor. *Ecotoxicology and Environmental Safety*. https://doi.org/10.1016/j.ecoenv.2020.111380
6. Devlamynck, R., de Souza, M. F., Michels, E., Sigurnjak, I., Donoso, N., & others. (2021). Agronomic and environmental performance of Lemna minor cultivated on agricultural wastewater streams—A practical approach. *Sustainability*., 13. https://doi.org/10.3390/su13031570
7. Fiordelmondo, E., Ceschin, S., Magi, G. E., Mariotti, F., & Iaffaldano, N. (2022). Effects of partial substitution of conventional protein sources with duckweed (Lemna minor) meal in the feeding of rainbow trout (Oncorhynchus mykiss) on growth performances and the quality product. *Plants*. https://doi.org/10.3390/plants11091220
8. Ghazali, F. & Kadir, S. T. (2026). Sustainable Governance of Transgenic Fish in Malaysia: Balancing Environmental Protection and Food Security. In F. Ghazali & S. Shukor (Eds.), Integrating Legal Compliance With Sustainable Development Goals (pp. 121-160). *IGI Global Scientific Publishing*. https://doi.org/10.4018/979-8-3373-1792-2.ch005
9. Habeeb, F., Majid, D., Makroo, H. A., Castagnini, J. M., Barba, F., & others. (2025). Duckweed as a sustainable protein source: Extraction methods, functional properties, and applications in food systems. *Food Chemistry*. https://doi.org/10.1016/j.foodchem.2025.145854
10. Herawati, V. E., Pinandoyo, Darmanto, Y. S., Rismaningsih, N., & Windarto, S. (2020). The effect of fermented duckweed (Lemna minor) in feed on growth and nutritional quality of tilapia (Oreochromis niloticus). *Biodiversitas*. https://doi.org/10.13057/biodiv/d210759
11. Nabi, N., Ahmed, I., Qadir, M., Reshi, Q.M. (2025). *Global Aquaculture: Scenarios and Nutritional Implications*. In: Ahmed, I., Ahmad, I. (eds) Aquaculture: Enhancing Food Security and Nutrition. Springer, Cham. https://doi.org/10.1007/978-3-031-92858-1_6
12. Obi, C., Dompreh, E. B., Manyise, T., Tan, S. H., Woo, S. P., & Rossignoli, C. M. (2025). Overview of the fishery and aquaculture sectors in Malaysia. *Frontiers in Sustainable Food Systems*, 9, Article 1545263. https://doi.org/10.3389/fsufs.2025.1545263
13. Osei, S. A., Ayisi, C. L., Boamah, G. A., & Mensah, G. D. (2025). The circular economy in aquaculture and fisheries: Enhancing sustainability and food security. *Circular Economy and Sustainability*. https://doi.org/10.1007/s43615-025-00632-1
14. Paolacci, S., Stejskal, V., & Jansen, M. A. K. (2021). Estimation of the potential of Lemna minor for effluent remediation in integrated multi-trophic aquaculture using synthetic aquaculture wastewater. *Aquaculture International*. https://doi.org/10.1007/s10499-021-00736-z
15. Paolacci, S., Stejskal, V., Toner, D., & Jansen, M. A. K. (2022). Integrated multitrophic aquaculture: Analysing contributions of different biological compartments to nutrient removal in a duckweed-based

water remediation system. *Plants*. https://doi.org/10.3390/plants11223103

16. Paolacci, S., Stejskal, V., Toner, D., & Jansen, M. A. K. (2022b). Wastewater valorisation in an integrated multitrophic aquaculture system: Assessing nutrient removal and biomass production by duckweed species. *Environmental Pollution*. https://doi.org/10.1016/j.envpol.2022.119059
17. Rifai, R. M., Yulistyorini, A., Siswahyudi, D., Pratiwi, J. R., & Fauzi, I. A. (2024). A kinetic approach for employing two duckweed species, Lemna minor and Spirodela polyrrhiza, in sustainable aquaculture wastewater treatment and fish feed production. *HAYATI Journal of Biosciences*. https://doi.org/10.4308/hjb.31.6.1223-1230
18. Song, Y., Hu, Z., Liu, S., Luo, S., He, R., Yang, X., Li, S., Yang, X., An, Y., & Lu, Y. (2025). Utilization of microalgae and duckweed as sustainable protein sources for food and feed: Nutritional potential and functional applications. *Journal of Agricultural and Food Chemistry*. https://doi.org/10.1021/acs.jafc.4c11610
19. Song, Y., Hu, Z., Yang, X., An, Y., & Lu, Y. (2026). Duckweed as a sustainable aquafeed: Effects on growth, muscle composition, antioxidant and immune markers in grass carp. *Animals*. https://doi.org/10.3390/ani16010053
20. Sońta, M., Rekiel, A., & Batorska, M. (2019). Use of duckweed (Lemna L.) in sustainable livestock production and aquaculture- A review. *Annals of Animal Science*. https://doi.org/10.2478/aoas-2018-0048
21. Sosa, D., Alves, F. M., Prieto, M. A., Pedrosa, M. C., Heleno, S. A., & others. (2024). Lemna minor: Unlocking the value of this duckweed for the food and feed industry. *Foods*. https://doi.org/10.3390/foods13101435
22. Takács, K., Végh, R., Mednyánszky, Z., Haddad, J., Allaf, K., & others. (2025). New insights into duckweed as an alternative source of food and feed: Key components and potential technological solutions to increase their digestibility and bioaccessibility. *Applied Sciences*. https://doi.org/10.3390/app15020884
23. Tan, S.-Y., Sethupathi, S., Leong, K.-H., & Ahmad, T. (2024). Challenges and opportunities in sustaining aquaculture industry in Malaysia. *Aquaculture International*, 32, 489–519. https://doi.org/10.1007/s10499-023-01173-w
24. Tavares, F. A., Lapolli, F. R., Roubach, R., Jungles, M. K., Fracalossi, D. M., & others. (2010). Use of domestic effluent through duckweeds and red tilapia farming in an integrated system. *Pan-American Journal of Aquatic Sciences*. https://panamjas.org/pdf_artigos/panamjas_5(1)_1-10.pdf
25. Waluyo, A., Satya, A., Nirmala, K., Hastuti, Y. P., Chrismadha, T., & others. (2024). The impact of shade net use on total nitrogen removal by duckweed (Lemna perpusilla) at different levels of catfish farming effluent. *Aquacultural Engineering*. https://doi.org/10.1016/j.aquaeng.2024.102456

Lecture notes

1. Duarte, I.D., Marín, R.R.C., Armenta, M.A.B. (2025). Evaluation of Lemna minor (Duckweed) as an Alternative Feed for Juvenile Colossoma macropomum (Black Pacu) During the Rearing Stage. In: Vilalta-Alonso, G., de Castro Pellegrini, C., Llanes-Santiago, O., Soto Pau, F., Radrigán-Ewoldt, R. (eds) Advances in Sciences Behind Food, Energy, and Innovation. *Lecture Notes on Multidisciplinary Industrial Engineering*. Springer, Cham. https://doi.org/10.1007/978-3-031-86954-9_29