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Sustainable Vannamei Shrimp Farming in Bonorowo, Indonesia Wetlands: Growth Performance, Land Suitability, and Ecological Challenges

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ABSTRACT

This study evaluated the land suitability, ecological sustainability, and growth dynamics of vannamei shrimp (*Litopenaeus vannamei*) aquaculture in the Bonorowo wetlands of Lamongan Regency, East Java, Indonesia. The research examines three topographical zones—shallow depression, middle valley, and deep swamp—across eight districts from October 2023 to January 2024, employing Multi-Dimensional Scaling (MDS) through the RAPFISH methodology and analyzing length-weight relationships (LWR) to assess growth patterns. Results revealed predominantly positive allometric growth (b > 3) across all wetland types, indicating that shrimp weight increases faster than length, though with varying degrees of correlation. Shallow wetlands demonstrated moderate correlation (R^2= 0.03–10%), middle wetlands showed more stable correlation (R^2= 2.8–3.2%), and deep wetlands exhibited high variability (R^2= 0.2–20%), reflecting diverse environmental conditions and resource competition. Land suitability analysis classified most regions as Very Suitable (S1) for aquaculture, with total scores ranging from 30 to 34, supported by favorable water quality parameters and suitable substrate conditions. However, ecological sustainability analysis revealed concerning trends, with sustainability indices falling below 50 points across all zones and cropping patterns. The fish-paddy-fish rotation system performed marginally better than other cropping patterns, though it was still categorized as unsustainable. Key factors influencing sustainability included feed availability, plant management, electrical energy access, stocking density, and disease management. The study identifies the need for wetland-specific interventions, including improved feed distribution systems in shallow depressions, enhanced pollution control in middle valleys, and better disease management strategies that balance productivity with ecological preservation—contributing to sustainable development in Indonesia's emerging aquaculture sector.

INTRODUCTION

The global food security landscape has been significantly transformed by the emergence of aquaculture as a vital source of protein, offering a sustainable alternative amid declining wild fish stocks. As capture fisheries face mounting pressure, aquaculture has evolved into a crucial sector that addresses food security concerns and catalyzes rural development and poverty alleviation **(Afandhi, 2020)**. This expansion has been particularly notable in Indonesia, which has become a major player in global aquaculture production. It has leveraged its extensive coastline, diverse aquatic ecosystems, and favorable climatic conditions to become a leading producer of shrimp, fish, and other aquaculture products.

The Lamongan Regency in East Java has emerged as a significant hub in Indonesia's aquaculture landscape, particularly in cultivating vannamei shrimp **(***Litopenaeus vannamei***)**. This species has gained prominence due to its remarkable adaptability and strong market demand. The region's success is evidenced by data from the Directorate General of Aquaculture, Ministry of Marine Affairs and Fisheries, Directorate General of Aquaculture, Ministry of Marine Affairs and Fisheries, 2021 which reported that Lamongan's fisheries sector generated an impressive production value of IDR 1.43 trillion in 2021, underscoring its substantial contribution to both regional and national economies.

The Bonorowo area of Lamongan Regency presents a unique agricultural ecosystem characterized by integrated farming systems that combine paddy cultivation with aquaculture. This integration has evolved through years of local adaptation to environmental conditions and resource limitations **(Afandhi, 2020)**. The system encompasses various rotation patterns, including paddy-shrimp, paddy-fish-shrimp, and dedicated aquaculture periods, enabling farmers to maximize land utilization while maintaining ecological balance. The paddy-shrimp rotation system is particularly innovative, with farmers cultivating paddy during the rainy season and converting fields to shrimp ponds during the dry season. This dual-purpose approach enhances land productivity and promotes sustainable practices, as shrimp waste is a natural fertilizer for subsequent paddy crops **(Afandhi, 2020)**.

However, the expansion and intensification of aquaculture operations in the region have given rise to significant sustainability challenges. Environmental degradation, water quality issues, and concerns about long-term system viability have become increasingly prominent. Disease outbreaks, often exacerbated by inadequate water management and overstocking, pose substantial risks to shrimp production. These challenges are compounded by socioeconomic pressures facing smallholder farmers, who often lack access to capital, technology, and market information, limiting their ability to implement sustainable practices **(Hardiana *et al.* 2024)**.

The rapid growth of aquaculture in Lamongan has also led to increased competition for land and water resources, potentially triggering conflicts between different user groups. This situation highlights the critical need for a comprehensive assessment of local ecosystem carrying capacity to prevent overexploitation and ensure long-term sustainability. To address these complex challenges, the RAPFISH **(**Rapid Appraisal for Fisheries**)** tool has emerged as a valuable methodology for evaluating sustainability across multiple dimensions **(Akhmaddin, 2023)**. RAPFISH has been adapted for aquaculture systems, originally designed to capture fisheries assessment, offering a structured framework considering ecological, economic, social, technological, and institutional factors.

This research aimed to contribute to the sustainable development of vannamei shrimp aquaculture in Lamongan Regency through three primary objectives. First, it seeks to evaluate the biophysical suitability of different farming patterns for vannamei shrimp cultivation in the Bonorowo area by assessing physical, chemical, and biological parameters **(Sugiarto, 2024)**. Second, it aims to conduct a comprehensive sustainability assessment of current farming practices using the RAPFISH methodology. Finally, it intends to develop an integrated sustainability model incorporating best practices and policy recommendations for future development **(Engle *et al.*, 2017)**.

This research is significant because it contributes to understanding the sustainability dynamics of integrated aquaculture systems in Indonesia. While previous studies have largely focused on the economic aspects of shrimp farming, there remains a critical gap in research examining sustainability's ecological and social dimensions in this context. The application of the RAPFISH tool represents a novel methodological approach to aquaculture sustainability assessment, offering valuable insights for policymakers, practitioners, and local communities **(Henriksson *et al.*, 2017)**.

The findings of this study have broad implications for the development of sustainable aquaculture practices not only in Lamongan but also in other regions facing similar challenges **(Lusiana *et al.*, 2018)**. The integrated sustainability model developed through this research can serve as a blueprint for promoting sustainable aquaculture practices, contributing to the broader goal of achieving sustainable and resilient food systems in Indonesia and beyond **(Akhmaddin *et al.*, 2023)**. By addressing the complex interplay of environmental, economic, and social factors, this research aimed to support the long-term viability of aquaculture while preserving ecological integrity and promoting social equity **(Senff *et al.*, 2018)**.

The sustainability of *Litopenaeus vannamei* shrimp farming in Bonorowo wetlands was investigated through three research purposes:

(1) to examine the influence of biophysical parameters and topographical variations (shallow depressions, middle valleys, deep swamps) on shrimp growth performance and land suitability; (2) to identify the ecological, socioeconomic, and institutional factors most critically degrading sustainability indices in integrated aquaculture-agriculture systems; and (3) to assess the potential enhancement of ecological resilience through

adaptive management strategies and technological innovations without compromising productivity.

MATERIALS AND METHODS

Research design

The location of this research is the Bonorowo area, which comprises three clusters: a shallow depression, a middle valley, and a deep swamp—all located in Lamongan Regency, East Java Province (Fig. 1a–c).

- The **shallow depression** cluster includes:
    - Laren District (**6°59′0.312″S 112°16′58.519″E**)
    - Maduran District (**7°0′25.95881″S 112°16′51.41705″E**)
    - Sekaran District (**7°1′36″S 112°16′17″E**)
- The **middle valley** cluster includes:
    - Karanggeneng District (**6°59′27″S 112°22′20″E**)
    - Kalitrengah District (**7°0′52″S 112°24′0″E**)
- The **deep swamp** cluster includes:
    - Turi District (**7°5′49.00175″S 112°22′26.29816″E**)
    - Karangbinangun District (**7°1′50″S 112°26′59″E**)
    - Glagah District (**7°3′0.34895″S 112°29′39.58476″E**)

The software used in this study includes Rap-Aquaculture Minapolitan for Multi-Dimensional Scaling (MDS) **(Gimpel *et al.*, 2018)**. Tools used during field surveys include refractometers, pH meters, DO meters, spectrophotometers, sample bottles, buckets, and stationery.

Materials for land suitability analysis consist of administrative maps of the Bonorowo area in Lamongan Regency. Materials for field observations include spectrophotometer kits, test water, and ice cubes.

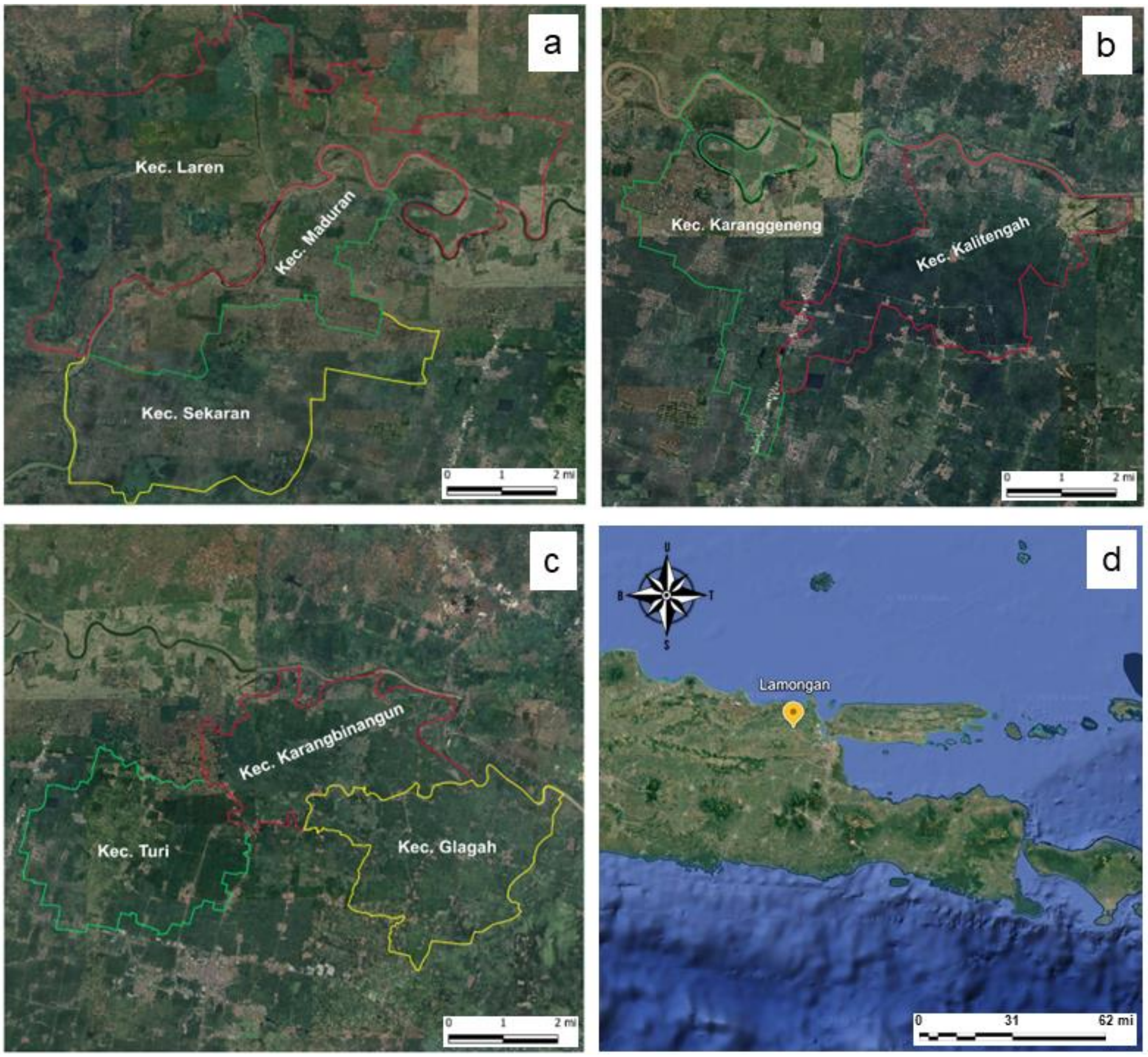

Fig. 1. The cluster of Bonorowo swamp condition to be **(**a**)** shallow depression; **(**b**)** middle valley shallow depression; **(**c**)** and a deep swamp; **(**d**)** Lamongan Regency, East Java Province, Indonesia

The sampling point is determined in an area that represents the research area, which is assumed to be a pond cultivation development area **(McSherry *et al.* 2023)**. According to **Xie *et al.* (2024)**, the technique for determining respondents using the Cluster Sampling approach is taking samples in groups. This study determined the research sample area in Bonorowo using three clusters, based on pond aquaculture activities with the following planting patterns:

- **Fish and shrimp – fish and shrimp – fish and shrimp**
- **Paddy – fish and shrimp – paddy**
- **Fish and shrimp – fish and shrimp – paddy**

These planting patterns were practiced using both traditional and traditional-plus methods across the Bonorowo area.

Shrimp growth analysis

The length-weight relationship describes the condition of shrimp and determines whether its growth is isometric or allometric **(Sudarno *et al.* 2018)**. According to **Effendi (2016)**, the general formulation used to calculate length-weight is isometric or allometric data of shrimp growth data, closely related to FCR and SGR data. FCR and SGR measurements were carried out using the following formula. A good FCR value in shrimp cultivation is 1.1-1.2.

$$W = aL^b \quad (1)$$

$$FCR = \frac{Feed\ Consumption}{W} \quad (2)$$

$$SGR = \frac{Wt - Wo}{t} x100 \quad (3)$$

Where, W is shrimp weight (g); L is total shrimp length (mm); a and b are the coefficient of the growth; SGR is daily growth rate (%); Wt is average weight of fish at the end of maintenance (tail); W_0 is Average weight of fish at the beginning of maintenance (tail); and t is length of maintenance (days).

Land suitability analysis

Scoring method

Scoring is based on the value of land according to its use, benefits or function. Each parameter has a different contribution to the level of suitability of pond land. According to **Suwarsito and Nirwansyah (2017)**, land suitability for vannamei shrimp pond cultivation is classified into 4 classes (Class S1: highly suitable, Class S2: moderately suitable, Class S3: marginally suitable, Class N: non-suitable). The scoring values of the environmental parameters for vannamei shrimp cultivation are presented in Table (1).

Referring to **Ikbal *et al.* (2019a)**, the division of class intervals is done by dividing the existing values into 2 classes of equal size (equal interval).

$$I = \frac{Nmax - Nmin}{K} \quad (4)$$

Where, I is interval of feasibility classes; K is number of feasibility classes determined; Nmax is total maximum weight value in location-I; and Nmin is total minimum weight value in location-i. The total score of the Shrimp Pond Land Suitability Scoring can be seen in the Table (2). The result of the range of the land suitability score were 9 – 15.75, 15.75 – 22.25, 22.5 – 29.25, 29.25 – 36 with the level of not suitable, marginally suitable, moderately suitable, high suitable, respectively **(Paldi *et al.*, 2021)**.

Table 1. Matrix of shrimp pond land characteristic parameters

Parameter	Score*			
	4	3	2	1
Temperature, °C	28 - 30	20 - 27, 31 – 35	12 - 19, 36 - 40	< 12 and > 40
pH	7.5 - 8.5	6.0 - 7.4, 8.6 - 9.5	4 - 5.9, 9.6 – 11	< 4 and > 11
Salinity, ppt	15 - 20	10 - 14, 21 - 30	< 10, 31 - 50	> 50
Soil pH	6.5 - 7.5	5.5 - 6.4, 7.6-8.0	4 - 5.4, 8.1 - 9	<4 and >9
DO, mg/L	5.1 - 7	4.1 - 5, 7.1 - 8	3.1 - 4, 8.1 - 10	< 3 and> 10
Nitrate, mg/L	0.9 - 3.5	0.3 - 0.8, 3.6 - 4.5	0.01 - 0.2, 4.6 – 5	<0.01 and >5
Phosphate, mg/L	> 0.21	0.1 - 0.20	0.05 - 0.09	<0.02
Sediment	Clayey Sandy Loam	Sandy Clay	Silty Clay	Mud, Sand, Gravel
Rain Intensity, mm/y	3000 - 2500	2499 - 2000	1999 – 1000, 2999 – 3500	<1000, >3500
Inundation Duration, month	< 3 month	3 - 6 month	6 month	> 6 month

*:1 (non-suitable); 2 (marginally suitable); 3 (Moderately suitable); 4 (Highly suitable).

Evaluation of cropping pattern model and sustainability multidimensional scaling (MDS) method

According to **Ferreira *et al.* (2015)**, to evaluate the sustainability of vannamei shrimp cultivation in the Bonorowo area, a non-metric multivariable method known as multi-dimensional scaling (MDS) was used. This analysis employed the Rap-Aquaculture Minapolitan tool, a modification of the RAPFISH (Rapid Assessment Techniques for Fisheries) methodology.

According to **Sugiarto *et al.* (2024)**, the sustainability status of vannamei shrimp aquaculture was clustered based on the distribution of MDS index values in the Minapolitan area development location, following KEPMEN KP 32/2010. The MDS index value ranges are categorized as follows:

- **0–50**: Not sustainable
- **50.01–60**: Less sustainable
- **60.01–70**: Quite sustainable
- **70.01–100**: Very sustainable

RESULTS AND DISCUSSION

Land suitability

Land suitability assessment is a systematic evaluation of land, classifying it into categories based on similarities in land type or quality that affect its appropriateness for cultivation. Depending on the available data, land suitability classification can be either quantitative or qualitative **(Artikanur, 2023)**. In the Bonorowo area, land suitability analysis is divided into three lowland zones based on elevation contour: shallow lowland, middle lowland, and deep lowland. Each parameter is first measured to obtain a suitability value, then scored according to defined standards. The total score is then matched to a corresponding land suitability level. The following are the observed land suitability parameters for each lowland zone in Bonorowo, Lamongan Regency **(Irawati, 2020)**.

Environmental data from the **shallow depression zones** reveal relatively stable values for most parameters, with Maduran District recording the highest average across the board compared to Laren and Sekaran. Water temperature in these districts shows moderate stability, with Sekaran exhibiting a narrower range (25.5–26.7°C), suggesting a more controlled microclimate **(Gorman, 2024)**. Water pH ranges from neutral to slightly alkaline (6.7–8.4), which supports aquatic ecosystem sustainability. The dominant soil type is clayey sandy loam, with moderate to poor drainage, affecting the area's resilience to prolonged waterlogging **(Evtimova, 2016)**.

Dissolved oxygen (DO) levels in Sekaran are higher (up to 7.6 mg/L), indicating better support for aquatic life than in other shallow depression zones **(Du *et al.*, 2023)**. Flood duration in Laren and Maduran is minimal, lasting only about one month. This short flooding period reduces waterlogging impact but also limits the development of a more robust wetland ecosystem **(Chao, 2021)**.

Table 2. Land suitability results for the shallow basin in Bonorowo region

Parameter	Turi	Glagah	Karang Binangun	Laren	Maduran	Sekaran	Kalitengah	Karang Gengeng
Temperature, °C	27.4-28	25.8-33	25.9-39.7	23.4-28.7	26-33	25.5-26.7	28.3-33	26.8-28.8
pH	7.4-8.4	7.9-8.1	7.4	7.0-7.4	7.3-8.3	7.3-7.7	7.2-7.6	6.7-7.8
Salinity, ppt	0-5	0	0-1	0	0	0-1	0	0-2
Soil pH	6.8	6.8	6.4	6.5-6.8	6.6	6.4	6.9	6.4-6.8
DO, mg/L	4.6-6.4	6.0-6.1	2.2-6.4	3-5.6	3.6-5.6	2.8-7.6	3.8-5.6	6.6-7.2
Nitrate, mg/L	0	0-10	0	0	0	0	0	0
Phosphate, mg/L	1.0-2.0	0.1-1.0	1.0-2.0	1	1.0-2.0	1.0-2.0	2	0.25-1.0
Sediment	Clayey Sandy Loam	Clayey Sandy Loam	Clayey Sandy Loam	Clayey Sandy Loam	Clayey Sandy Loam	Clayey Sandy Loam	Clayey Sandy Loam	Clayey Sandy Loam
Rain	1239	1239	1239	1330	1196	1196	1330	1196

Intensity, mm/th								
Inundation Duration, month	5	5	5	1	1	1	3	3

The middle valley zones, including Karanggeneng and Kalitengah, demonstrate moderate environmental conditions. Water temperatures in Kalitengah (28.3– 33°C) and Karanggeneng (26.8– 28.8°C) remain relatively high and consistent. Water pH in Karanggeneng (6.7– 7.8) and Kalitengah (7.2– 7.6) indicates neutral to slightly alkaline conditions essential for sustaining aquatic ecosystems. Similar to the shallow depression zones, the soil in these districts is clayey sandy loam, with moderate water retention and drainage capacity. However, the flood duration in both areas is slightly longer, during three months, allowing for developing semi-permanent wetland ecosystems that support diverse aquatic and terrestrial life **(Akhmaddin, 2023)**.

Table 3. Measurement of the suitability score of shallow lowland land in the Bonorowo area

Parameter	Turi	Glagah	Karang Binangun	Laren	Maduran	Sekaran	Kalitengah	Karang gengeng
Temperature	3	4	3	3	4	3	4	3
pH	4	4	3	3	4	3	4	4
Salinity	2	2	2	2	2	2	2	2
Soil pH	4	4	3	4	4	4	4	3
DO	3	4	3	3	3	4	3	4
Nitrate	3	4	3	3	3	3	2	2
Phosphate	4	3	4	4	4	4	4	3
Sediment	4	4	4	4	4	4	4	4
Rain Intensity	2	2	2	2	2	2	2	2
Inundation Duration, month	3	3	3	4	4	4	3	3
Total Score	32	34	30	32	34	33	32	30

The deep swamp zones exhibit the most dynamic environmental conditions, with Turi, Karangbinangun, and Glagah showing significant variations. Water temperatures are notably high in Karangbinangun (25.9– 39.7°C), potentially influenced by intense solar radiation and anthropogenic factors, while Turi and Glagah show slightly lower but still varied temperature ranges **(Gorman, 2024)**. Water pH is slightly alkaline in Turi (7.4– 8.4) and Glagah (7.9– 8.1), but Karangbinangun maintains more stable levels (7.4).

The soil in these areas, predominantly clayey sandy loam, plays a crucial role in water retention during the prolonged flooding period of five months **(Evtimova, 2016)**. This extended inundation fosters the development of unique wetland ecosystems and increases the risk of soil and water quality degradation. Dissolved oxygen **(**DO**)** in Karangbinangun is notably low (2.2 mg/L), indicating potential oxygen stress for aquatic life in this deep swamp region **(Du *et al.* 2023)**.

Across all clusters, nitrate was detected only in Glagah (0–10 mg/L), while phosphate was more evenly distributed, ranging from 1–2 mg/L in most locations, with lower levels observed in Glagah (0.1–1 mg/L) and Karanggeneng (0.25–1 mg/L). These variations reflect differences in anthropogenic inputs such as agricultural runoff and domestic waste. Flood durations significantly influence each cluster. Shallow depressions (Laren, Maduran, Sekaran) experience the shortest flooding periods (1 month), middle valleys (Karanggeneng, Kalitengah) experience moderate durations (3 months), while deep swamps (Turi, Karangbinangun, Glagah) are inundated for five months. These differences necessitate tailored management strategies that balance ecological preservation with human needs, particularly for fish farming and sustainable wetland utilization. Comparing these environmental parameters with fish farming standards allows for scoring each sub-districts suitability, guiding future resource management in the Bonorowo swamp region of Lamongan Regency **(Hendrajat, 2018)**.

The shallow depression zones generally scored within the range of 32–34, classifying them as highly suitable for fish farming **(Duarah, 2020)**. Maduran District achieved the highest total score (34), indicating excellent environmental conditions, including optimal water pH (4), soil pH (4), and flood duration (4), which support aquatic ecosystems. Sekaran, with a score of 33, also falls into the highly suitable category, with its strength being dissolved oxygen (4) **(Muddassir *et al.* 2016)**. While achieving a score of 32, Laren remains highly suitable, with consistent contributions from parameters such as phosphate levels (4) and sediment substrate (4). These results suggest that shallow depression areas are ideal for sustainable aquaculture with minimal intervention **(Paudel, 2021)**.

In the middle valley cluster, Kalitengah and Karanggeneng scored 32 and 30, respectively, placing them between moderately suitable and highly suitable **(Jayanthi, 2018)**. Kalitengah’s high scores in pH (4), soil pH (4), and phosphate levels (4) demonstrate its potential, though slightly lower scores in nitrate (2) and rainfall intensity (2) reflect challenges related to nutrient availability and water dynamics . Karanggeneng’s score of 30, categorized as moderately suitable, indicates the need for improvements, particularly in nitrate levels (2) and salinity (2), to enhance its suitability for aquaculture **(Tarunamulia *et al.*, 2024)**.

The deep swamp zones generally performed well, with Turi scoring 32, Karangbinangun scoring 30, and Glagah achieving 34. Turi and Glagah are highly suitable, benefiting from strong scores in water pH, soil pH, phosphate levels, and sediment substrate. Glagah's superior score reflects optimal conditions, particularly in dissolved oxygen (4) and nitrate levels (4). Karangbinangun, scoring 30 and classified as moderately suitable, faces challenges due to lower salinity (2) and dissolved oxygen (3) scores, which may require interventions such as improved water circulation or aeration systems **(Sonkamble *et al.*, 2019)**.

The land suitability assessment in the Bonorowo region indicates highly favorable conditions for aquaculture, with total scores ranging from 30 to 34. Most locations were classified as moderately to highly suitable, with only Karanggeneng and Karangbinangun scoring at the lower end **(**30**)**, highlighting the need for targeted management strategies, such as salinity control and oxygen level improvement, to enhance their aquaculture potential **(Jayanthi, 2021)**. Key factors contributing to the region's high suitability include favorable water quality parameters such as pH, dissolved oxygen, and nutrient availability and the dominant sandy clay loam substrate, which provides stability and water retention for pond construction **(Boyd *et al.* 2020)**. According to **Ahmed (2019)**, flood durations, ranging from one to five months depending on land elevation and contour, further support the region's potential for sustainable shrimp and fish farming. Overall, the shallow, middle, and deep lowlands in Bonorowo achieved a Very Suitable (S1) classification, underscoring the area's promise as a hub for aquaculture development.

Shrimp growth

The length-weight relationship **(**LWR**)** analysis of fish across shallow, middle, and deep wetlands in Bonorowo, Lamongan Regency, highlights distinct growth patterns influenced by environmental conditions **(Safran, 1992)**. Predominantly positive allometric growth (b>3b) was observed in all wetland types, indicating that fish gain weight faster than they grow in length. In shallow wetlands such as Laren, Maduran, and Sekaran Districts (Fig. 2d-f), R^2 values ranged from 0.03% to 10%, reflecting a low correlation between length and weight **(Famoofo, 2020)**. This variability suggests diverse environmental conditions, fluctuating water levels, and inconsistent food availability, affecting growth patterns. To improve growth consistency, it is essential to enhance water management, stabilize food resources, and maintain suitable habitat conditions **(Sutarjo, 2021)**.

In middle wetlands, the LWR analysis in Kalitengah and Karanggeneng (Fig. 2g-h) Districts showed R^2 values of 2.8% and 3.2%, indicating a more stable but modest correlation. Despite the relatively low explanatory power of length in predicting weight, the positive allometric growth points to favorable conditions that promote fish development **(Fu, 2018)**. According to **Poormahdi (2018)**, maintaining water depth, controlling sediment quality, and managing nutrient loads are critical for preserving these growth trends. Meanwhile, deep wetlands in Turi, Glagah, and Karangbinangun (Fig. 2 a-c) districts revealed higher variability, with R^2 values ranging from 0.2 to 20%. Karangbinangun stood out with the strongest correlation (R^2= 20%), suggesting optimal conditions for fish growth, while other districts may face environmental stressors such as fluctuating water quality and resource competition.

These findings provide valuable insights for fisheries management and aquaculture optimization. The positive allometric growth observed across districts reflects promising growth potential, but the variability in R^2 highlights the need to address underlying environmental factors **(Luna & Cobo, 2020)**. According to **Dey *et al*. (2016)**, wetland-specific management strategies, such as regular water quality monitoring, habitat restoration, and integrated aquaculture systems, are essential to improve fish growth consistency and resource efficiency. According to **Sanon and Melcher (2021)**, developing adaptive strategies that consider seasonal variability and environmental influences will support sustainable aquaculture in Bonorowo while preserving wetland ecosystems for long-term productivity.

MDS-Rapfish analysis for the sustainability of aquaculture

MDS-Rapfish is an essential analytical tool for evaluating regional sustainability based on ecology. The MDS-RAPFISH technique produces two primary outputs. The first is the RAPFISH Ordination, which ranks and positions objects in a multidimensional space based on input values of assessed attributes. This output generates scores that can be used to measure the sustainability status of a fish farming operation or a specific area. The second output is the Leverage of Attributes, which refers to the contribution of attributes to the sustainability score of a region **(Rendrarpoetri *et al.*, 2024)**. The leverage of attributes output allows for the identification of the characteristics that significantly influence the overall sustainability assessment of a fish farming operation or region. This analysis technique was applied in three areas based on the height contour: deep lowland, middle lowland, and shallow lowland **(Parmawati & Hardyansah, 2020)**. Each region has characteristics in the form of different planting patterns and fishery cultivation commodities (Table 4).

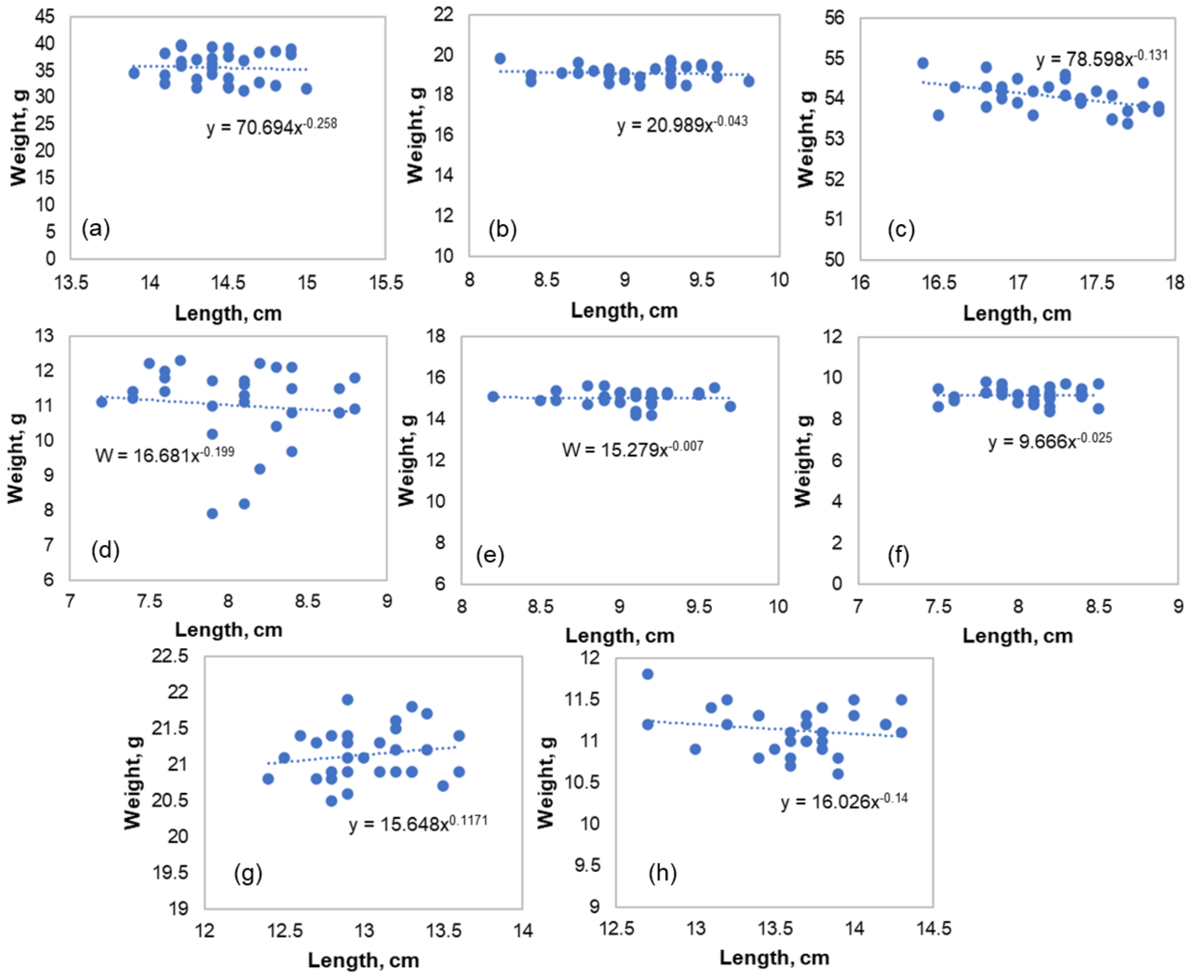

Fig. 2. Length-weight relationship of fish conducted in three types of wetlands (shallow, middle, and deep) in (a) Turi, (b) Glagah, (c) Karang Binangun, (d) Laren, (e) Maduran, (f) Sekaran, (g) Kalitengah, (h) Karang genggeng district

Table 4. Planting patterns of simulation model

Region	Planting Patterns		
	Fish – Fish – Fish	Fish – Paddy	Fish – Fish – Paddy
Shallow depression	-	Shrimp, Milk Fish	Shrimp, Milk Fish, Tilapia
Middle valley	Shrimp, Milk Fish, Tilapia	-	Shrimp, Milk Fish, Tilapia
Deep swamp	Shrimp, Milk Fish, Tilapia	Shrimp, Milk Fish, Tilapia	Shrimp, Milk Fish

Ecological dimension

The analysis of ecological sustainability in deep swamp revealed two main planting patterns: fish-paddy-fish and fish-paddy. The fish-paddy-fish pattern includes vannamei shrimp, milkfish, and tilapia, while the fish-paddy pattern focuses on shrimp and milkfish **(Ahmed & Turchini, 2020)**. Sustainability assessments using the MDS-RAPFISH method showed that the fish-paddy-fish pattern had a poor sustainability score of 40.08, categorized as unsustainable, with contributing factors such as plant management, feed availability, electrical energy fulfillment, and stocking density. The fish-paddy planting pattern showed a slightly better score of 51.32, categorized as less sustainable, with significant attributes including plant management, feed availability, seed availability, and pollutant input **(Zhang *et al*., 2021)**.

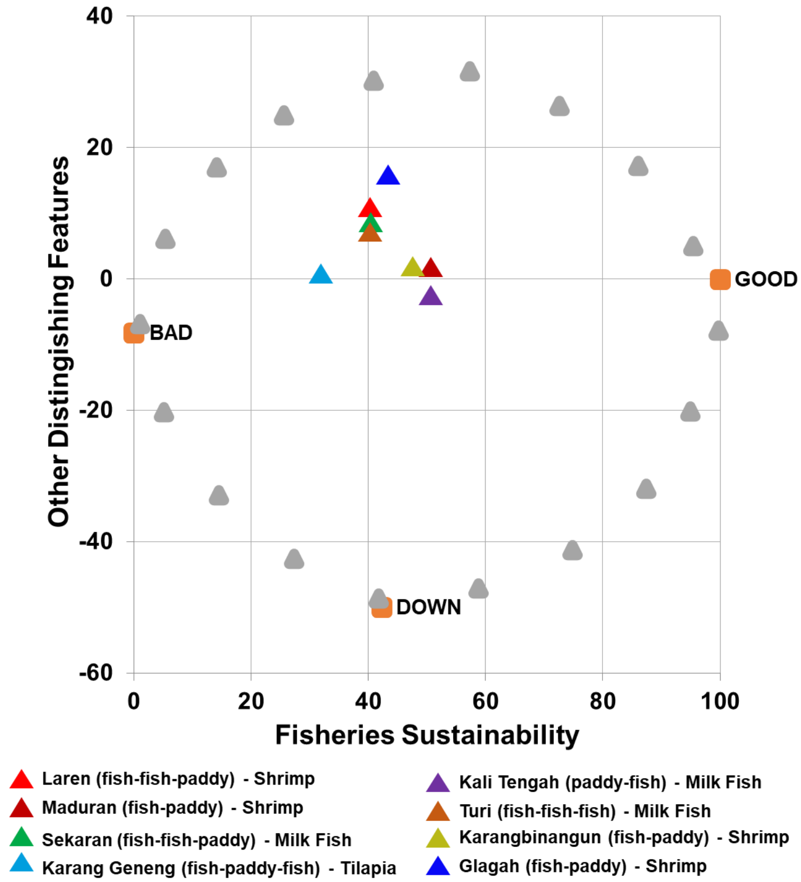

Fig. 3. MDS-RAPFISH ecology of fisheries sustainability result for every district assessed by planting pattern

In the middle valley, the fish-fish-fish and fish-fish-paddy patterns were implemented, with shrimp farming in the fish-fish-fish pattern scoring a sustainability index of 36.13, categorized as unsustainable. According to **Ahmed and Turchini (2021)**, key contributing factors included feed availability, stocking density, plant management, and electrical energy availability. The fish-fish-paddy pattern had a slightly better sustainability score of 47.75 but fell under the unsustainable category. Shrimp farming, milkfish, and tilapia showed better ecological sustainability in the fish-fish-paddy pattern. Milkfish scored 29.15 in the fish-fish-fish pattern, and tilapia scored 28.04, while in the fish-fish-paddy pattern, milkfish scored 44.64 and tilapia 37.08.

In Shallow, all three cropping patterns (fish-fish-fish, fish-paddy, and fish-fish-paddy) are applied, with tilapia as the primary commodity in the fish-fish-paddy pattern. Shrimp farming in the fish-paddy-fish pattern had a poor sustainability score of 42.68, while the fish-fish-fish pattern showed a slightly better score of 44.32. However, both patterns still fell under the unsustainable category, with critical attributes like plant management, electrical energy availability, stocking density, and feed availability contributing to sustainability. The fish-paddy pattern had the lowest score at 40.81, with fry availability and flooding also being significant factors for sustainability **(Rahman & Ahmed, 2021)**.

The findings across the three areas highlight that vannamei shrimp farming consistently exhibits better ecological sustainability than milkfish and tilapia. However, all commodities in all planting patterns and regions still fall below the 50-point threshold for sustainability, indicating that improvements are needed. Attributes such as feed availability, plant management, electrical energy, and stocking density must be addressed, along with region-specific challenges like flooding and pollutant input **(Poli *et al.*, 2019)**. These results emphasize the need for targeted interventions, strategic planning, and adaptive management tailored to each cropping pattern and environmental condition to ensure the long-term sustainability of aquaculture in the Bonorowo region.

The ecological conditions in the districts within the shallow depression area exhibit varying characteristics by assessing the Root Mean Square change (RMS), as shown in Fig. (4a - i). RMS is ordination when a selected attribute is removed from a sustainability scale of 0 – 100 **(Bertassello, 2020)**. Laren recorded high scores in electricity availability (5.17), stocking density (5.34), and water quality (5.88), although it was deficient in disease incidence (1.53). Maduran excelled in water quality (9.04) and disease incidence (6.47) but was weak in feed availability (2.33) and seed availability (2.47). In Sekaran, the strength was in feed availability (4.65), but disease incidence (0.18) posed a significant challenge. Overall, this group faces challenges in ensuring the equitable distribution of resources, especially in ecosystem health and biological resources **(Zhang *et al.*, 2023)**.

In the middle valley region, the districts of Karanggeneng and Kalitengah demonstrate different management potential. Karanggeneng scored highest in stocking density (6.50) and electricity availability (4.87), but was very low in seed availability (0.47) and water quality (0.38). On the other hand, Kalitengah excelled in electricity availability (7.33), plant management (5.34), and feed availability (4.24), though it was weak in pollutant input (1.61). This condition suggests that the middle valley group requires improved pollution control and access to essential resources to support better environmental sustainability **(Prihadi & Pasaribu, 2024)**.

The deep swamp area, which includes the districts of Turi, Karangbinangun, and Glagah, presents more extreme ecological conditions. Turi recorded the highest scores in electricity availability (8.64) and stocking density (4.67), but was very weak in seed availability (3.01) and disease incidence (0.12). Karangbinangun had the highest score for electricity availability (9.74) but was low in disease incidence (0.04). Meanwhile, Glagah recorded low scores across most parameters, with the highest score only in stocking density (5.72). According to **Yule (2010)**, the main challenge for this group is improving disease resistance and ensuring better water quality to support the preservation of swamp ecosystems.

The three categories of swamp conditions in Bonorowo reveal different management needs. The shallow depression group requires improvements in ecosystem health and resource distribution **(Ismail, 2017)**. The middle valley group needs efforts to reduce pollution and enhance access to vital resources. Meanwhile, the deep swamp group must focus on disease management and improving water quality **(Anthonj, 2016)**. An integrated management plan that considers the specific characteristics of each group is essential to ensure the overall environmental sustainability of the Bonorowo swamp.

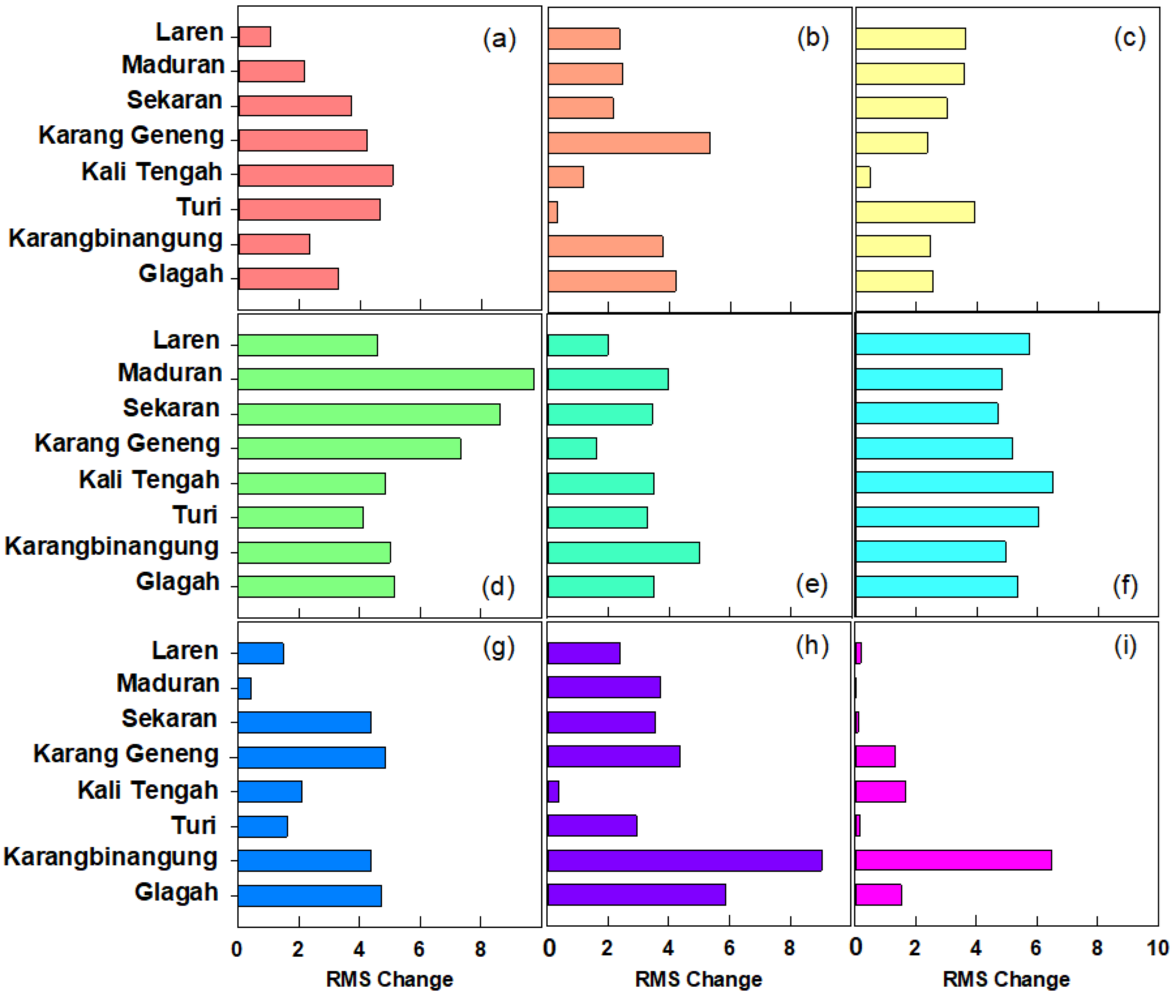

Fig. 4. Leverage of attribute of (a) Feed availability, (b) Plant management, (c) Seed availability, (d) Electricity supply sufficiency, (e) Stocking density, (f) Pollutant entry, (g) Flood occurrence, (h) Water quality, and (i) Disease incidence

The recapitulation of important ecological attributes in shrimp farming in the Bonorowo area shows several main factors influencing environmental sustainability. Feed availability and crop management emerged as the most frequently considered attributes, with a frequency of seven times each across all areas and cropping patterns. This indicates that adequate feed availability and good crop management are critical factors that contribute significantly to the sustainability of shrimp farming **(Ahmed, 2017)**. All areas (Middle valley, shallow depression, and deep swamp) and all cropping patterns (Fish-Fish-Paddy, Fish- Paddy, and Fish-Fish) recognized the importance of these two factors.

Table 5. Recapitulation of leverage of attributes of the ecological dimensions of vannamei shrimp cultivation in the Bonorowo area, Lamongan Regency

Atribute Social	Fish - Fish - Paddy			Fish - Paddy		Fish - Fish - Fish		Freq
	Middle Valley	Shallow	Deep swamp	Shallow	Deep swamp	Shallow	Deep swamp	
Feed availability	v	v	v	v	v	v	v	7
Plant management	v	v	v	v	v	v	v	7
Electricity supply sufficiency		v	v	v		v	v	5
Stocking density		v	v	v		v		4
Seed availability	v				v		v	3
Pollutant Source					v			1
Flood occurrence	v							1

Another attribute of note was the availability of fry, which occurred three times in the Fish-Fish-Paddy and Fish-Fish cropping patterns in deep swamp and shallow depression **(Eissa, 2022)**. According to **Kumaran *et al.* (2020)**, pollutant inflow and flooding occurred only once each, indicating that although necessary, these issues may be less frequent or localized to certain areas. Pollutant inflow was recorded in the Fish-Paddy cropping pattern in the deep swamp, while flooding was reported in the Fish-Fish-Paddy cropping pattern in the middle valley. In conclusion, factors such as feed availability, crop management, electrical energy, stocking density, and fry availability are key aspects that must be managed well to improve the ecological sustainability of shrimp farming in this area.

CONCLUSION

This study highlights the high land suitability **(**S1 classification**)** for vannamei shrimp cultivation across Bonorowo's wetlands but underscores critical ecological challenges, including low sustainability indices (<50) due to feed scarcity, pollution, and disease risks. To address these, tailored management strategies are essential: optimizing feed distribution in shallow depressions, enhancing pollution control in middle valleys, and implementing biosecurity protocols with regulated stocking densities in deep swamps. Integrating the fish-paddy-fish rotation system can further bolster sustainability by balancing aquaculture with agriculture. Technology and innovation are pivotal in bridging productivity and ecological preservation—IoT sensors and automated feeders optimize resource use, while RAPFISH-driven data platforms enable real-time monitoring of growth and disease risks. Renewable energy solutions like solar-powered aeration reduce grid dependency and pollution, and coupling these advancements with farmer training ensures equitable adoption. By merging region-specific interventions with smart technologies, Bonorowo can elevate sustainability indices beyond the critical threshold, securing resilient, eco-friendly shrimp farming as a cornerstone of Indonesia's aquaculture future.

Conflicts of interest

We have no conflicts of interest to disclose.

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