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ECONOMIC DYNAMICS OF MARINE FINFISH AQUACULTURE IN SABAH, MALAYSIA: PRODUCTION TRENDS AND PRICE ELASTICITY OF SUPPLY (2011–2022)

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ABSTRACT

The marine aquaculture sector in Sabah, Malaysia has significantly contributed to economic growth, food security, and employment opportunities for coastal communities. This study analysed production and price trends in marine finfish aquaculture in Sabah from 2011 to 2022, focusing on culture systems, species composition, and market dynamics. Cage culture, particularly for groupers (Epinephelidae), contributed the most to total finfish production. Mann-Kendall trend analysis revealed significant negative production trends and rising prices across most systems and species, indicating a supply-demand imbalance. Groupers exhibited inelastic supply, highlighting challenges in scaling production to meet market changes while Asian seabass (*Lates calcarifer*) demonstrated elastic supply despite declining output. Fluctuating production of snappers (*Lutjanus* spp.) and humphead wrasse (*Cheilinus undulatus*), due to limited seed availability and reliance on wild-caught or imported juveniles, raised sustainability concerns. The COVID-19 pandemic disrupted market access and logistics, leading to production declines and price volatility, though subsequent recovery demonstrated the sector's resilience. These findings emphasise the urgent need for strategic interventions to stabilise production, manage price volatility, and reduce dependency on wild-caught juveniles. Further investments in hatchery technologies, disease management, and sustainable farming practices are crucial in ensuring the long-term sustainability and continued economic growth of Sabah's aquaculture sector.

Introduction

Global fisheries and aquaculture production reached a record high of 223.2 million tonnes in 2022, marking a 4.4% increase from 2020 (The Food and Agriculture Organisation of the United Nations [FAO], 2024). As global fisheries resources continue to decline (FAO, 2022), aquaculture has emerged as a critical solution to meet the growing demand for aquatic food. In 2022, aquaculture surpassed capture fisheries as the primary source of aquatic animals, with finfish accounting for 65.2% of global aquaculture production (FAO, 2024). This shift highlights the growing importance of aquaculture in addressing food security, supporting economic development, and reducing the pressure on wild fisheries.

In Malaysia, aquaculture has grown significantly, from 0.21 million tonnes in 2006 (Department of Fisheries Malaysia, 2007) to 0.57 million tonnes in 2022 (Department of Fisheries Malaysia, 2023). The industry has evolved from traditional practices in the 1920s to incorporate semi-intensive and intensive methods, driven by government-led initiatives and private investments (Hashim, 2024). Sabah, a Malaysian state in northern Borneo renowned for its rich marine biodiversity, contributed approximately 0.31 million tonnes of marine and brackish water production in 2022, valued at US$0.12 million (Department of Fisheries Malaysia, 2023).

As of 2023, marine finfish aquaculture in Sabah comprised 128 ponds (58.83 hectares), 9,504 cages (57.25 hectares), and 1,602 pens (28.03 hectares). This reflects the substantial physical footprint and diversity of culture systems employed across the state (Department of Fisheries Sabah, 2024). The sector is predominantly composed of small- to medium-scale farms that rely on sheltered coastal areas for cage and pen culture systems (Mohd Khatib, 2015; Wong *et al*., 2018), supporting the cultivation of high-value finfish species such as groupers (Harun *et al.*, 2024).

As a region with significant potential for aquaculture growth, Sabah offers valuable insights into balancing economic development with sustainability and food security. However, its aquaculture sector faces significant challenges, including inconsistent seed supply, environmental sustainability issues, disease outbreaks, and market fluctuations, all of which threaten its long-term viability (Wong *et al*., 2018; Tan *et al*., 2023). Addressing these challenges requires a detailed understanding of production trends, price dynamics, and the adaptability of producers to market changes.

Trend analysis plays a critical role in identifying patterns of growth or decline, which can help forecast production capacities and address underlying issues such as disease outbreaks, environmental degradation, or inefficiencies in farming practices (Aripin *et al*., 2020; Mohd Idris *et al*., 2022; Tan *et al*., 2023). Similarly, price trends offer insights into market behaviour and volatility, enabling stakeholders to develop pricing strategies that balance profitability and affordability (Olsen *et al*., 2008; Pernet & Browman, 2021). Estimating the price elasticity of supply is equally vital for understanding how producers respond to market changes. Elastic supply reflects producers' ability to quickly adjust output to price fluctuations, thereby maintaining market stability and profitability. Conversely, inelastic supply suggests potential risks of shortages or surpluses that could destabilise markets.

This study aims to analyse the economic dynamics of marine finfish aquaculture in Sabah, Malaysia between 2011 and 2022. The specific objectives are: (1) to examine historical production and price trends across marine and brackish water finfish culture systems, identifying significant patterns of growth, decline, or fluctuation over time; and (2) to evaluate the price elasticity of supply for marine finfish species cultured using cage, pen, and pond systems, providing insights into producers' responsiveness to price changes and implications for policy and management. The findings will also explore the challenges and opportunities associated with marine finfish culture in Sabah. These objectives collectively aim to enhance understanding of Sabah's marine finfish aquaculture sector and support the development of evidence-based strategies for sustainable growth, economic resilience, and food security.

Materials and Methods

Data Description

The data for this study comprised secondary data from 2011 to 2022, obtained from the Department of Fisheries Sabah, Malaysia. The dataset includes estimates of production and value for marine and brackish water finfish, categorised by culturing systems and species at the district level. In this study, "value" refers to the total production value in Malaysian Ringgit or United States dollars while "price" denotes the average unit price per kilogramme of fish (US dollars per kilogramme after conversion). The culture systems included were cage, pen, and pond culture. The species covered in the data belonged to five main groups: (1) Groupers

(Epinephelidae), (2) Asian seabass (*Lates calcarifer*), (3) snappers (*Lutjanus* spp.), (4) humphead wrasse (*Cheilinus undulatus*), and (5) others. Grouper species recorded in the dataset included mouse grouper (*Cromileptes altivelis*), giant grouper (*Epinephelus lanceolatus*), tiger grouper (*E. fuscoguttatus*), spotted coral grouper (*Plectropomus leopardus*), and other groupers. The TGGG hybrid grouper (tiger grouper, *Epinephelus fuscoguttatus* ♀ × giant grouper, *E. lanceolatus* ♂) was classified under "other groupers" prior to 2018 but was categorised separately from 2018 onwards. Snapper species included the mangrove snapper (*Lutjanus argentimaculatus*) and red snapper (*Lutjanus bohar*). Species grouped under "other" categories included *Carangoides* spp., *Scomberoides* spp., and *Siganus* spp.

The original dataset recorded the prices of marine and brackish water finfish in Malaysian Ringgit. To ensure comparability for international readers, all price data were converted to US dollars using a fixed exchange rate. This fixed rate was derived as the average DEC Alternative Conversion Factor across the period from 2011 to 2022, obtained from the World Development Indicators database maintained by the World Bank. This approach was chosen to mitigate distortions caused by fluctuations in exchange rates, as prices in Malaysian Ringgit are relatively stable. By standardising the conversion rate, we aimed to present consistent and reliable price data, thereby reducing the impact of exchange rate volatility on the analysis.

Data Analysis

Two main analyses were employed: The Mann-Kendall test for trend analysis and the log-linear regression model for estimating the price elasticity of marine finfish supply. Both analyses were performed at the aggregate level (utilising all data) and at the disaggregate level (utilising specific groups of data). The analyses were further specified by three commonly used marine aquaculture culture systems (cage, pen, and pond culture systems) and by four main marine finfish groups (i.e., groupers, Asian seabass, snappers, and humphead wrasse), based on data availability.

Mann-Kendall Trend Test for Production and Price Trends

The Mann-Kendall trend test is a non-parametric statistical method used to identify trends in time series data. It is particularly useful for detecting monotonic upward or downward trends without assuming a specific data distribution. This test evaluates the presence of a trend by analysing the difference in signs between earlier and later data points, which helps determine whether data values consistently increase or decrease over time. The Mann-Kendall trend test is advantageous for datasets with non-normal distributions or missing values, it does not require the data to be linear. It is widely applied in various fields, including hydrology, climatology, and environmental science, to assess trends in variables such as temperature, precipitation, and pollutant concentrations. In aquaculture, the Mann-Kendall trend test can be used to analyse trends in finfish production and water quality parameters over time, helping to identify significant changes that may impact aquaculture practices and sustainability (Hipel & McLeod, 1994; Libiseller & Grimvall, 2002).

The Mann-Kendall trend test calculates Kendall's tau by comparing all possible pairs of data points to determine the number of concordant and discordant pairs. Kendall's tau quantifies the strength and direction of a monotonic trend in a time series. The Kendall's tau statistic (*r*) is calculated as follows:

$$\tau = \frac{C-D}{\sqrt{(C+D+T_x)(C+D+T_y)}} \tag{1}$$

where C is the number of concordant pairs, D is the number of discordant pairs, T_x is the number of tied ranks in X, and T_y is the number of tied ranks in Y. A positive τ value indicates a positive monotonic trend; negative τ indicates a negative monotonic trend. The value ranges from -1 to 1, where 1 indicates a perfect positive trend, -1 indicates a perfect negative trend, and 0 indicates no monotonic trend. To assess if the trend is statistically significant at the 5% level of significance, the tau value is first converted to a Z-score using the formula below:

$$Z = \frac{\tau}{\sigma_\tau} \quad (2)$$

where σ_τ is the standard deviation of Kendall's tau, which can be approximated based on the sample size and the number of ties in the data. The Z-score is then used to find the p-value from the standard normal distribution. The p-value represents the probability of observing a test statistic as extreme as, or more extreme than, the one observed, assuming the null hypothesis is true. The null hypothesis states that there is no monotonic trend in the data and the alternative hypothesis states that there is a monotonic trend (positive or negative) in the data. The null hypothesis will be rejected if the p-value is less than 0.05.

Linear Regression for Price Elasticity

Log-linear regression analysis is a powerful tool for estimating the own price elasticity of supply, which measures the responsiveness of the quantity supplied to changes in price. By transforming both the dependent variable (quantity supplied) and the independent variable (price) into their natural logarithms, this method linearises the multiplicative relationship between these variables, making it easier to interpret the elasticity directly from the regression coefficient.

The coefficient obtained from the log-linear model represents the elasticity, indicating the percentage change in quantity supplied for a 1% change in price. This approach is particularly useful in economic studies where the relationship between variables is not strictly linear. In agricultural economics, log-linear regression has been used to estimate the supply elasticity of various crops, providing insights into how farmers adjust their production in response to price changes (Gujarati & Porter, 2009; Wooldridge, 2015). Accurate estimation of supply elasticity is crucial for policymakers to design effective interventions that stabilise markets and ensure sustainable production levels.

To estimate price elasticity of supply, we performed a log-linear regression model with yearly production (tonnes) as the dependent variable and price (US dollars/kg) as the only independent variable in the model:

$$lnQ = \beta_0 + \beta_1 lnP + \epsilon \quad (3)$$

where InQ is the natural log of production, InP is the natural log of price, β_0 and β_1 are the parameters, and ϵ is the error term. The Ordinary Least Squares (OLS) method is used to estimate the parameters (β_0, β_1). β_1 represents the elasticity of supply with respect to the own price (P). Values greater than 1 indicate elastic responses (sensitive to price changes) while values less than 1 indicate inelastic responses.

Results

Composition of Production across Culture Systems and Finfish Groups

The composition of marine finfish production in Sabah varied across the three aquaculture systems over the study period (Figure 1). Cage culture consistently served as the dominant production system, although its proportional contribution exhibited a decreasing trend. Prior to 2020, cage culture contributed between 69% and 90% of total marine finfish production. From 2020 onwards, it remained the primary production system but accounted for a reduced share, ranging between 45% and 64% of the total production.

Pond culture's contribution to total production remained relatively minor throughout the study period, ranging from 2.6% to 16.0%, with most years showing less than 10% contribution. In contrast, pen culture demonstrated notable growth after 2016, surpassing pond culture in terms of proportional contribution and continuing to increase thereafter.

Breaking down the composition by finfish groups, groupers dominated production in both cage and pen culture systems, whereas Asian seabass was the primary species cultivated in pond culture (Figure 2). In years when TGGG

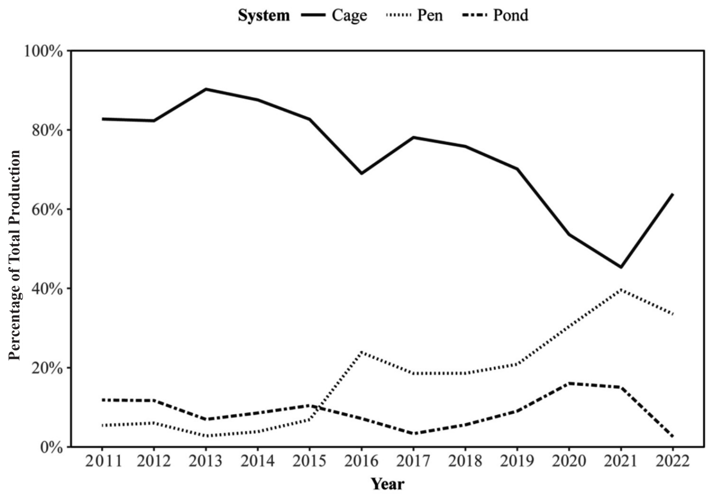

Figure 1: Percentage contribution of cage, pen, and pond culture systems to the total marine finfish production in Sabah from 2011 to 2022

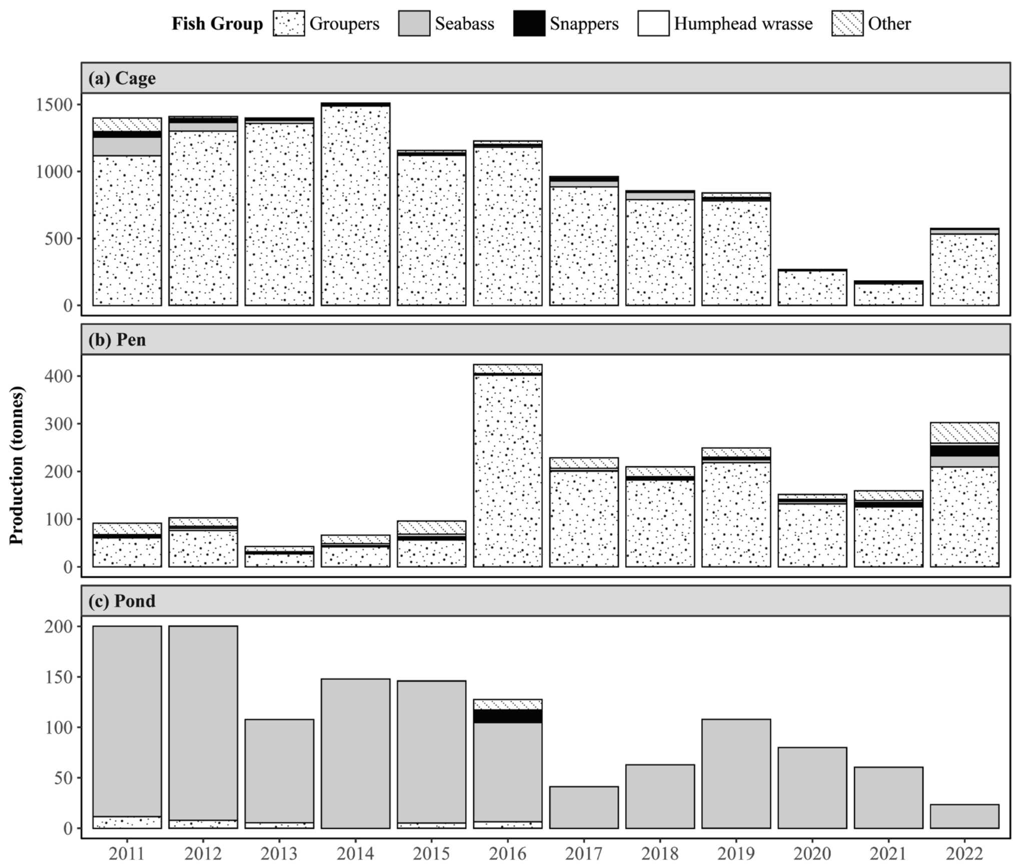

Figure 2: Finfish group composition in terms of actual production (tonnes) within cage, pen, and pond culture systems in Sabah from 2011 to 2022

hybrid grouper was reported separately from other groupers, it accounted for over 74% of the total grouper production. From 2017 onwards, Asian seabass became the sole species produced in pond culture. Snappers were predominantly cultured in cage and pen systems, with pond culture only reporting snapper production in 2016. Humphead wrasse, on the other hand, was exclusively cultured in cage and pen systems and was absent from pond culture throughout the study period. Other finfish species were preferentially cultivated in pen culture systems.

Production and Price Trends

The production and price trends of marine finfish aquaculture in Sabah from 2011 to 2022 demonstrate significant fluctuations across different culture systems (Figure 3) and finfish groups (Figure 4). Trend analysis using Kendall's tau provides statistical insights into these changes (Tables 1 & 2).

Overall finfish production exhibited a significant negative trend (Kendall's tau = -0.673, $p < 0.05$; Table 1), indicating a decline in output over the study period. Production peaked at 1,779.62 tonnes in 2016 but dropped to 402.52 tonnes in 2021 before partially recovering to 901.05 tonnes in 2022 [Figure 3 (a)]. In contrast, prices displayed a significant positive trend (Kendall's tau = 0.491, p < 0.05), rising from US$9.26 per kilogramme in 2011 to US$11.38 in 2022, despite some variability [Figure 3 (a)].

Cage culture production exhibited a significant negative trend (Kendall's tau = -0.818, $p < 0.05$; Table 1), declining from a peak of 1,510 tonnes in 2014 to a low of 182.59 tonnes in 2021, with partial recovery to 565.39 tonnes in 2022 [Figure 3 (b)]. Prices displayed a significant positive trend (Kendall's tau = 0.491, $p < 0.05$; Table 1), increasing from US$8.39 per kilogramme in 2011 to US$10.70 in 2022 [Figure 3 (b)].

Pen culture production showed no significant trend (Table 1), although it increased overall from 91.60 tonnes in 2011 to 302.28 tonnes in 2022, with some fluctuations [Figure 3 (c)]. Prices exhibited a significant positive trend (Kendall's tau = 0.527, $p < 0.05$; Table 1),

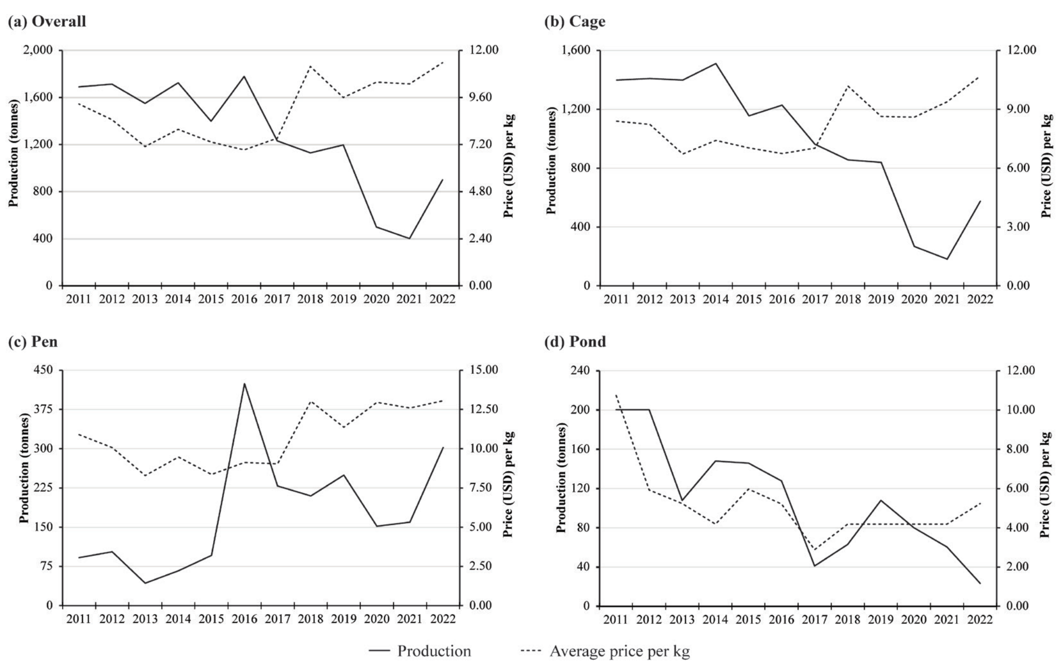

Figure 3: Production and price trends of marine and brackish water finfish aquaculture in Sabah from 2011 to 2022, categorised by system: Overall, cage, pen, and pond

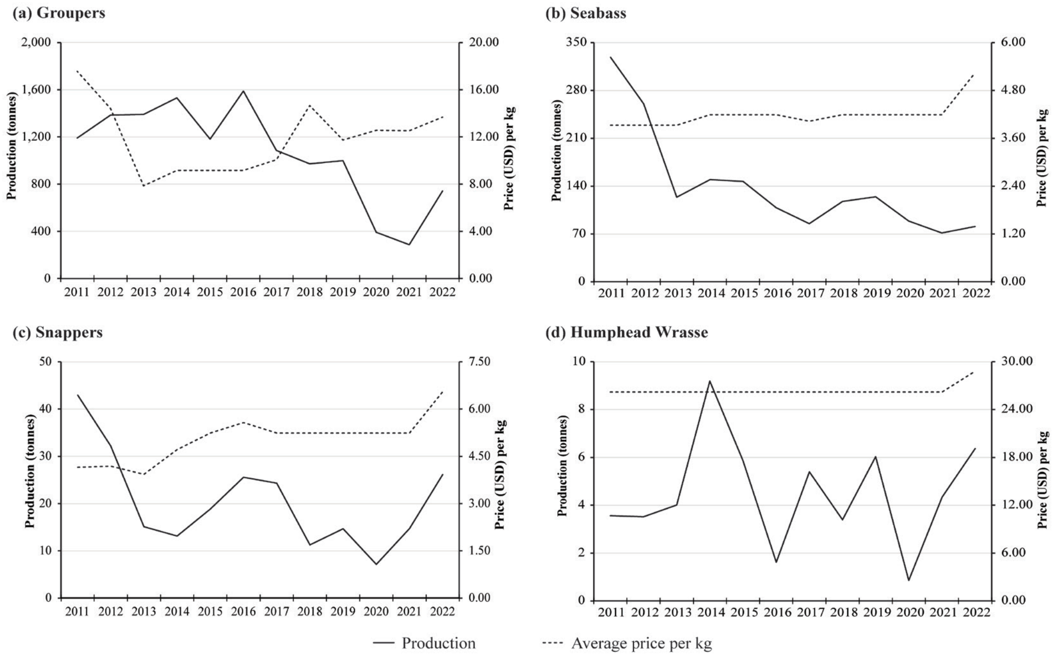

Figure 4: Production and price trends of groupers (Epinephelidae), Asian seabass (*Lates calcarifer*), snappers (*Lutjanus* spp.), and humphead wrasse (*Cheilinus undulatus*) in Sabah from 2011 to 2022

Table 1: Trend analysis for production and price of marine finfish by culture system for the period 2011 to 2022

Group of Data	Variable	Kendall's tau	Trend
All culture systems	Production trend	-0.673*	Negative trend
	Price trend	0.491*	Positive trend
Cage culture system	Production trend	-0.818*	Negative trend
	Price trend	0.491*	Positive trend
Pen culture system	Production trend	0.418	No trend
	Price trend	0.527*	Positive trend
Pond culture system	Production trend	-0.636*	Negative trend
	Price trend	-0.285	No trend

*Significant at 0.05 level of significance

increasing from US$10.89 per kilogramme in 2011 to US$13.05 in 2022 [Figure 3 (c)].

Pond culture production showed a significant negative trend (Kendall's tau = -0.636, $p < 0.05$; Table 1), decreasing from 200.3 tonnes in 2011 to 23.38 tonnes in 2022 with notable year-to-year variability [Figure 3 (d)]. Prices remained stable, with no significant trend (Table 1). However, prices varied during the study period, dropping sharply from US$10.74 per kilogramme in 2011 to US$2.88 in 2017 before stabilising between US$4.19 and US$5.24 in subsequent years [Figure 3 (d)].

Table 2: Trend analysis for production and price of marine finfish by finfish group for the period of 2011 to 2022

Group of Data	Variable	Kendall's tau	Conclusion
Grouper (Epinephelidae)	Production trend	-0.673*	Negative trend
	Price trend	0.491*	Positive trend
Asian seabass (*Lates calcarifer*)	Production trend	-0.636*	Negative trend
	Price trend	-0.285	No trend
Snapper (*Lutjanus* spp.)	Production trend	-0.818*	Negative trend
	Price trend	0.491*	Positive trend
Humphead wrasse (*Cheilinus undulatus*)	Production trend	0.418	No trend
	Price trend	0.527	Positive trend

*Significant at 0.05 level of significance

In terms of finfish groups, groupers production exhibited a significant negative trend (Kendall's tau = -0.673, p < 0.05; Table 2), peaking at 1,589.26 tonnes in 2016 and declining to 286.43 tonnes in 2021 and recovering to 741.71 tonnes in 2022 [Figure 4 (a)]. Prices displayed a significant positive trend (Kendall's tau = 0.491, p < 0.05; Table 2), decreasing from US$17.55 in 2011 to US$13.67 in 2022, despite earlier volatility [Figure 4 (a)].

Asian seabass production exhibited a significant negative trend (Kendall's tau = -0.636, p < 0.05; Table 2), declining from 328.51 tonnes in 2011 to 80.93 tonnes in 2022, with slight fluctuations [Figure 4 (b)]. Prices showed no significant trend (Table 2), remaining stable around US$4.19 per kilogramme for most years until a sharp increase to US$5.24 in 2022 [Figure 4 (b)].

Production of snappers showed a significant negative trend (Kendall's tau = -0.818, p < 0.05; Table 2), declining from 42.93 tonnes in 2011 to a low of 7.13 tonnes in 2020, with partial recovery to 26.14 tonnes in 2022 [Figure 4 (c)]. Prices displayed a significant positive trend (Kendall's tau = 0.491, p < 0.05; Table 2), gradually increasing from US$4.15 per kilogramme in 2011 to US$6.55 in 2022 [Figure 4 (c)].

Humphead wrasse production exhibited no significant trend (Table 2), fluctuating throughout the study period. Production started at 3.56 tonnes in 2011, peaked at 9.19 tonnes in 2014, dropped to a low of 0.86 tonnes in 2020, and partially recovered to 6.37 tonnes in 2022 [Figure 4 (d)]. Prices showed a significant positive trend (Kendall's tau = 0.527, p < 0.05), remaining stable at US$26.20 per kilogramme until increasing to US$28.82 in 2022 [Figure 4 (d)].

Price Elasticity of Supply

The price elasticity of supply for marine finfish in Sabah's aquaculture sector from 2011 to 2022 was analysed across different culture systems and finfish groups (Table 3). Elastic supply indicates that a 1% change in price results in a more than proportional change in the quantity supplied while inelastic supply reflects limited responsiveness to price changes.

All individual culture systems displayed elastic supply, with elasticity values greater than 1. However, none of these specific models achieved statistical significance in their fit (Table 3). Overall, aggregating all culture systems, the supply was also elastic, with a statistically significant model fit (R^2 = 0.40, $F(1, 10)$ = 6.67, p < 0.05).

For finfish groups, Asian seabass and humphead wrasse exhibited elastic supply, though neither model was statistically significant (Table 3). In contrast, groupers and snappers showed inelastic supply, indicating limited responsiveness to price changes. The

Table 3: Price elasticity of supply across different culture systems and finfish groups from 2011 to 2022

Group of Data	Estimated Regression Model	t Statistic of Price Effect	R square	Price Elasticity of Supply
All culture systems	$\widehat{lnQ}$ = 13.11-1.72lnP	-2.58*	0.40	Elastic
Cage culture system	$\widehat{lnQ}$ = 14.78-2.34lnP	-2.04	0.29	Elastic
Pen culture system	$\widehat{lnQ}$ = -0.96+1.61lnP	1.48	0.18	Elastic
Pond culture system	$\widehat{lnQ}$ = 1.18+1.14lnP	2.11	0.31	Elastic
Grouper (Epinephelidae)	$\widehat{lnQ}$ = 9.63-0.73lnP	-1.10	0.11	Inelastic
Snapper (*Lutjanus* spp.)	$\widehat{lnQ}$ = 4.65-0.59lnP	-0.54	0.03	Inelastic
Asian seabass (*Lates calcarifer*)	$\widehat{lnQ}$ = 13.11-2.99lnP	-1.81	0.25	Elastic
Humphead wrasse (*Cheilinus undulatus*)	$\widehat{lnQ}$ = -24.87+5.69lnP	0.79	0.06	Elastic

$\widehat{lnQ}$ is natural log of production and is natural log of price
*Significant at 0.05 level of significance

R-squared values varied across models, with some explaining only a small portion of the variability in supply, suggesting the influence of additional factors on production.

Discussion

Dynamics of Production and Finfish Group Composition across Culture Systems

The dominance of the cage culture system in Sabah's marine finfish aquaculture sector can be attributed to its suitability for cultivating high-value species, particularly groupers, and Sabah's geographical advantage of having an extensive coastline and favourable marine conditions for cage farming. Cage culture is also relatively easier and cheaper to set up compared to other systems (Sadovy, 2000; Wong *et al.*, 2018; Harun *et al.*, 2024), making it particularly attractive for small- to medium-scale farms, which dominate Sabah's aquaculture sector (Mohd Khatib, 2015).

Groupers are highly valued for their quality and taste, leading to sustained market demand and higher prices compared to most other farmed finfish species (Glamuzina & Rimmer, 2022). The introduction of the TGGG hybrid grouper (*Epinephelus fuscoguttatus* × *E. lanceolatus*) further boosted grouper production in Sabah, particularly through cage farming (Department of Fisheries Malaysia, 2023), due to its rapid growth, resilience, and favourable taste profile (Ch'ng & Senoo, 2008; Bunlipatanon & U-taynapun, 2017; Ching *et al.*, 2018; Shapawi *et al.*, 2019). Reflecting this demand, the area of cage farming in Sabah expanded from 11.5 hectares in 2006 (Department of Fisheries Malaysia, 2007) to 57.2 hectares in 2022 (Department of Fisheries Malaysia, 2023).

However, the contribution of cage culture to total production has declined since 2020. This reduction can be attributed to a combination of external shocks such as the COVID-19 pandemic and the increasing contribution of pen culture. High-value species like groupers were particularly affected during the pandemic due to disrupted market access and reduced consumer purchasing power (FAO, 2020; Azra *et al.*, 2021), leading to a decline in production.

Pen culture offers several advantages over cage culture, including sturdiness, suitability for shallower depths, and resistance to damage from strong winds and waves (Ransangan *et al.*, 2012; Wong *et al.*, 2018). These characteristics, combined with the system's ability to support mixed-species cultivation, likely encouraged producers to adopt this method to diversify their production and mitigate risks associated with reliance on a single system or species. However, pen culture also has some disadvantages compared to cage culture, including longer construction times (Wong *et al*., 2018) and reduced flexibility in terms of location (Harun *et al*., 2024).

Pond culture, although contributing minimally to total finfish production, plays a critical role in the cultivation of Asian seabass. Asian seabass is a fast-growing and hardy species with broad environmental tolerances, making it well-suited for pond farming, which typically involves static water systems compared to cage or pen culture (Philipose *et al*., 2010; Khan *et al*., 2021; Nhan *et al*., 2022). The specialisation of pond culture in Asian seabass production from 2017 onwards suggests a deliberate strategy by producers to optimise available facilities, allocating pond facilities for hardier species while reserving cages and pens for high-value species.

These interdependencies between culture systems and the species they support highlight the importance of aligning farming practices with the biological and economic characteristics of target species. Cage and pen cultures remain critical for high-value species like groupers, snappers, and humphead wrasse while pond culture provides a stable platform for Asian seabass production. These dynamics emphasise the adaptive strategies employed by producers to maximise productivity while responding to market demands, environmental constraints, and external shocks.

Interdependence of Production, Price Trends, and Cultivated Species

The trends in production and pricing of marine finfish in Sabah from 2011 to 2022 demonstrate a strong interdependence between culture systems, cultivated species, and market dynamics. Significant negative trends in production and positive trends in prices (Mann-Kendall trend analysis) across most systems and species emphasise the need for targeted interventions to stabilise production and manage price volatility.

Groupers, cultivated predominantly in cage and pen systems, exhibited inelastic supply, highlighting the difficulties in scaling production quickly in response to market shifts. Key challenges in grouper production included low larval survival, diseases, reliance on diminishing supplies of trash fish for feed, and poor water quality (Rimmer & Glamuzina, 2019; Ariff *et al*., 2019; Ybanez Jr. & Gonzales, 2023). The decline in grouper production, particularly after the COVID-19 pandemic, further highlights these limitations.

In contrast, Asian seabass demonstrated elastic supply, suggesting that producers could respond more readily to price changes. Despite this flexibility, Asian seabass production generally declined throughout the study period. Factors such as cannibalism, inconsistent supply of quality fry, diseases, and economic shifts have been identified as significant challenges in Asian seabass culture (Philipose *et al*., 2010; Ransangan *et al*., 2012; Aripin *et al*., 2020; Islam *et al*., 2023). Additionally, some producers may have shifted to higher value species such as hybrid groupers TGGG in cage and pen systems or prawns in pond systems (Harun *et al*., 2024), contributing to the decline in Asian seabass production.

Production trends for snappers and humphead wrasse showed significant fluctuations, with relatively stable prices. These patterns suggest that factors beyond price may be influencing production. Snapper fry production in Sabah remains very limited (Department of Fisheries Malaysia, 2023). While successful seed production of humphead wrasse has been achieved in Indonesia and Japan, challenges persist in broodstock management and larval rearing (Slamet & Hutapea, 2005; Hirai *et al*., 2013). To date, there have been no successful attempts to produce humphead wrasse seeds in Malaysia. Consequently, aquaculture operations for both snappers and humphead wrasse in Sabah rely heavily on wild-caught or imported juveniles for grow-out farming to meet market demand, raising significant sustainability concerns.

The COVID-19 pandemic (2020–2022) profoundly disrupted global aquaculture systems, leading to reduced market demand and logistical capacity (FAO, 2020; van Senten *et al*., 2021; Lebel *et al*., 2021; Islam *et al*., 2021). In Malaysia, national lockdowns caused reduced market demand and logistical constraints, resulting in oversupply and subsequent price declines (Azra *et al*., 2021). These disruptions align with the production declines observed in Sabah during this period, particularly for groupers and Asian seabass. Local aquaculture operators in Kudat reported sales losses during the pandemic, which led to reduced production levels (Rosle Rabiu & Wong Sin Hin, pers. comm.). Nonetheless, the subsequent recovery in production and prices demonstrates the resilience of Sabah's aquaculture sector. These disruptions highlight the vulnerability of aquaculture systems to external shocks and underscore the critical need for resilient production strategies and robust supply chains.

Broader Implications for Aquaculture Development in Sabah

The findings of this study highlight both opportunities and vulnerabilities within Sabah's aquaculture sector. While Sabah's geographical and environmental advantages have facilitated the growth of marine aquaculture, the observed production declines and reliance on high-value species expose vulnerabilities that must be addressed for sustainable development.

The dominance of groupers in cage and pen systems and Asian seabass in pond culture reflects a high degree of specialisation. While this approach has enabled producers to capitalise on market demand for these species, it also increases vulnerability to market fluctuations, disease outbreaks, and environmental changes. Expanding the diversity of cultured species, particularly for pond systems could help distribute risks more evenly. For example, promoting the culture of compatible species alongside Asian seabass in pond systems could enhance productivity and economic resilience (Aripin *et al*., 2020).

While pen culture has shown promise as an alternative to cage culture for high-value species, its growing popularity necessitates careful management to ensure sustainable expansion. Unlike cage systems, pen culture has disadvantages in terms of construction time (Wong *et al*., 2018) and location flexibility (Harun *et al*., 2024). To ensure sustainability, technological innovations such as integrated multi-trophic aquaculture could be explored to diversify production within pen systems while minimising environmental impacts (Mustafa *et al*., 2017; Tan *et al*., 2023).

The dependency on wild-caught juveniles for snappers and humphead wrasse culture raises significant sustainability concerns, particularly given the fluctuating production trends observed in this study. The humphead wrasse is listed as an Endangered species on the International Union for Conservation of Nature (IUCN) Red List and included in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES Appendix II), highlighting the ecological implications associated with wild capture. Over-reliance on wild stocks not only impacts population stability but also creates market uncertainties tied to natural fluctuations in supply. Investing in hatchery development and improving seed production for these species is critical for reducing ecological impacts and stabilising production outputs to ensure long-term sustainability.

Strategic policies and investments are essential to balance economic growth with environmental sustainability in Sabah's aquaculture sector. Support for small-scale producers, who constitute the majority of the aquaculture industry (Mohd Khatib, 2015; Wong *et al*., 2018) should be prioritised through capacity-building programmes, financial assistance, and access to affordable technologies (Tan *et al*., 2023). Incentivising sustainable practices through certification programmes could also encourage producers to adopt eco-friendly approaches (Manap & Pauzi, 2020). Furthermore, investments in research and development to improve disease diagnostics, prevention, and treatment methods are critical, given their impact on both production and market stability (Tan *et al*., 2023).

Limitations of the Study

While this study provides insights into the production and price trends of marine finfish aquaculture in Sabah, several limitations must be acknowledged. Firstly, the reliance on secondary data may introduce reporting errors, inconsistencies, or gaps. Examples include the inconsistent separation of hybrid groupers from other groupers in earlier years and the lack of differentiation between wild-caught and hatchery-produced finfish.

Secondly, this study primarily focused on production and price trends without incorporating external drivers such as environmental changes, disease outbreaks, policy shifts, or technological advancements. All these factors are likely to have significantly influenced production (Wong *et al*., 2018; Tan *et al*., 2023) but were not analysed due to data limitations.

Additionally, the study did not account for feed costs, which are a major operational concern and significantly affect profitability in marine finfish aquaculture. Lastly, the use of aggregate data and average prices may obscure variability among individual producers and culture systems, potentially masking important market dynamics and system-specific challenges.

Conclusions

The findings of this research shed light on the complexities and trends within Sabah's marine finfish aquaculture sector, particularly the relationships between culture systems, species selection, and market dynamics. The study highlights the challenges posed by the dominance of high-value species such as groupers, snappers, and humphead wrasse, the vulnerabilities associated with these species' reliance on market demand and external factors. While cage and pen culture systems remain central to production, there is a clear need for diversification, improved hatchery technologies, and resilient supply chains to ensure long-term sustainability. Fostering innovation within production systems is also crucial to balance economic growth with ecological responsibility.

Strategic investments in research, disease management, and capacity building for small-scale producers will be essential to support the continued growth of Sabah's aquaculture sector. By adapting to these evolving challenges and opportunities, the sector can contribute more effectively to food security, economic growth, and sustainable development in the region. This research supports the advancement of the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 14 (Life Below Water), by promoting sustainable aquaculture practices and resilient food systems.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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