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# STRUCTURAL VULNERABILITY OF DUAL-MODE LOGISTICS IN BALI TUNA EXPORTS: AN STL, ARIMA, AND MITSA APPROACH

# KERENTANAN STRUKTURAL LOGISTIK DUAL-MODA EKSPOR TUNA BALI: PENDEKATAN STL, ARIMA, DAN MITSA

**Charles Paulinus Marulitua Sitanggang[1*], Taryono[1,2], Joko Santoso[1,3]**
[1]Study Program of Agro-Maritime Logistics, IPB University, Jl. Agatis, IPB Dramaga Campus, Bogor 16680, Indonesia
[2]Department of Aquatic Resources Management, Faculty of Fisheries and Marine Sciences, IPB University, Jl. Agatis, IPB Dramaga Campus, Bogor 16680, Indonesia
[3]Department of Aquatic Product Technology, Faculty of Fisheries and Marine Science, IPB University, Jl. Agatis, IPB Dramaga Campus, Bogor 16680, Indonesia
*Corresponding author: charlessitanggang@apps.ipb.ac.id

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## ABSTRACT

Bali's tuna export logistics system relies on two modes: belly cargo flights and direct shipping, which are vulnerable to policy disruptions. This study aims to: (1) analyze quantitative changes in PSBB and PPKM policies on the volume and value of Balinese tuna exports; (2) examine the relationship between air logistics capacity and export performance and explain export volume and value divergence; and (3) evaluate the structural recovery capacity of the Balinese tuna export logistics system in the post-pandemic period. Data from October 2016 to June 2023 were analyzed using Seasonal-Trend decomposition Loess (STL), Auto Regressive Integrated Moving Average (ARIMA), and Multiple Interrupted Time Series Analysis (MITSA) with Newey-West correction. MITSA confirmed that April 2020 PSBB caused a decline in export value of -USD 7,718,352 ($p = 0.0000829$***), while July 2021 Emergency PPKM resulted in a divergence: export volume remained relatively stable while export value exhibited a sustained downward trend, indicating economic pressure that was not reflected by export volume. International flight data at I Gusti Ngurah Rai Airport confirmed a -99.7% collapse during the PSBB1 phase, with regression showing a strong relationship between flight frequency and export value ($r = 0.923$; $p < 0.001$). The disruption of sea transportation was confirmed by Meratus Line's decision to suspend services from Benoa Port (blank sailings) since April 2020. The findings indicate a structural shift in Bali's dual-modal logistics system, from an efficient mode to a defensive mode. Data-driven logistics strategies and national policies are needed to restore competitiveness of Indonesian fisheries exports.

Keywords: cold chain, dual-mode logistics, logistics resilience, structural vulnerability, tuna export

## ABSTRAK

Sistem logistik ekspor tuna Bali bergantung pada dua moda penerbangan: *belly cargo* dan pelayaran langsung yang rentan terhadap disrupsi kebijakan. Penelitian ini bertujuan untuk: (1) menganalisis perubahan kuantitatif kebijakan PSBB dan PPKM terhadap volume dan nilai ekspor tuna Bali; (2) menguji hubungan kapasitas moda logistik udara dengan kinerja ekspor serta menjelaskan divergensi volume dan nilai ekspor; dan (3) mengevaluasi kapasitas pemulihan struktural sistem logistik ekspor tuna Bali pada periode pasca-pandemi. Data dari Oktober 2016–Juni 2023 dianalisis menggunakan *Seasonal-Trend decomposition Loess* (STL), *Auto Regressive Integrated Moving Average* (ARIMA), dan *Multiple Interrupted Time Series Analysis* (MITSA) dengan koreksi Newey-West. MITSA mengonfirmasi bahwa PSBB April 2020 menyebabkan penurunan level nilai ekspor sebesar -USD 7.718.352 ($p = 0{,}0000829$***), sedangkan PPKM Darurat Juli 2021 menghasilkan divergensi: volume ekspor relatif stabil, sementara nilai ekspor menunjukkan kecenderungan penurunan yang persisten, mengindikasikan tekanan ekonomi yang tidak tercermin hanya dari volume ekspor. Data penerbangan internasional Bandara I Gusti Ngurah Rai mengonfirmasi *collapse* -99,7% pada fase PSBB1, dengan regresi menunjukkan hubungan kuat antara frekuensi penerbangan dan nilai ekspor ($r = 0{,}923$; $p < 0{,}001$). Disrupsi moda laut dikonfirmasi melalui keputusan Meratus Line menghentikan layanan dari Pelabuhan Benoa (*blank sailings*) sejak April 2020. Temuan menunjukkan indikasi perubahan struktural pada sistem logistik dual-moda Bali, dari mode efisien menuju mode defensif. Diperlukan strategi logistik berbasis data dan kebijakan nasional untuk memulihkan daya saing ekspor perikanan Indonesia.

Kata kunci: ekspor tuna, kerentanan struktural, logistik dual-moda, rantai dingin, resiliensi logistik

## INTRODUCTION

The disruption of global supply chains caused by the COVID-19 pandemic exposed structural weaknesses in the logistics system for perishable commodities. Ivanov (2020) introduced the concept of the ripple effect in supply chain disruptions, in which disruptions at one logistics node propagate throughout the entire distribution network. In the context of seafood logistics, fresh seafood is particularly vulnerable to transportation disruptions because of its limited shelf life and strict cold-chain requirements (Love *et al.* 2021; FAO 2022). Consistent with this, FAO (2022) reported that seafood exports from developing countries declined by an average of 15–25% during 2020, with fresh products being approximately twice as affected as frozen products.

In the ASEAN context, Vietnam and Thailand, Indonesia's major competitors in the global tuna market, demonstrated relatively greater resilience during the COVID-19 pandemic, reflecting differences in cold-chain infrastructure and export logistics capacity (FAO 2022). Thailand, supported by its larger processing industry and more established cold-chain logistics, recovered more rapidly in canned and frozen tuna exports (FAO 2022). In contrast, Bali's tuna exports relied heavily on international passenger flights (belly cargo) for premium fresh tuna, making them more vulnerable to disruptions in air transportation, as reflected in the export and flight data analysed in this study. Research by Sitanggang *et al.* (2025) confirms that a logistics strategy based on optimizing air freight is a top priority for the recovery of Balinese tuna exports, outperforming sea freight and combined land-sea freight alternatives in terms of delivery time and reliability.

Most previous studies on the impact of the pandemic on Indonesian fisheries exports used a descriptive-comparative approach or simple linear regression without considering the time series nature of the data. Kristiani *et al.* (2023) analyzed the performance of Indonesia's processed tuna exports to Japan using Revealed Comparative Advantage (RCA) but were unable to capture the causal effects of specific policy interventions. Rahmawati *et al.* (2017) studied the dynamics of longline tuna fisheries using the CPUE approach without integrating logistics or government policy variables. Studies using Interrupted Time Series Analysis (ITSA) are well established for public health policy evaluation (Bernal *et al.* 2017), but their application to export fisheries logistics under multiple non-pharmaceutical interventions, such as PSBB and PPKM, remains very limited.

Based on the literature review, there are three research gaps that have not been answered. First, there are no studies that quantitatively measure the multi-phase causal impact of Large-Scale Social Restrictions (PSBB-Pembatasan Sosial Berskala Besar) and Community Activity Restrictions (PPKM-Pemberlakuan Pembatasan Kegiatan Masyarakat) on the volume and value of Indonesian tuna exports using a robust time series approach. Second, the economic mechanisms behind the divergence between relatively stable export volumes and declining export values, reflecting the degradation of added value due to the shift from fresh to frozen products, have never been tested empirically based on time series data. Third, the role of air and shipping logistics mode capacity as a mediating variable in a dual-modal logistics system has never been integrated in a policy evaluation model for Bali tuna exports.

Based on these research gaps, this study formulates three main questions: (1) What is the quantitative impact of each phase of social restriction policies on the level and trend of Balinese tuna export volume and value? (2) What economic mechanisms explain the divergence between stagnant export volume and declining export value during the Emergency PPKM phase? (3) Does Balinese tuna export's dual-modal logistics system show signs of structural recovery post-pandemic, and what are its projections in the medium term.

This study aims to: (1) analyze the quantitative changes in each phase of the PSBB and PPKM policies on Balinese tuna export volume and value; (2) examine the relationship between air logistics capacity and export performance and explain the mechanisms of export volume and value divergence; and (3) evaluate the structural recovery capacity of the Balinese tuna export logistics system in the post-pandemic period. This study contributes to the literature through three aspects: (1) the application of MITSA with six simultaneous non-pharmaceutical policy intervention points to Indonesian perishable commodity export data; (2) the integration of real-world logistics data—flight frequency and confirmed blank sailings on the Meratus Line—as empirical evidence of the mode disruption mechanism; and (3) an extension of Ivanov's (2020) ripple effect framework by showing that in a dual-mode perishable supply chain, disruptions in the dominant mode are not only associated with volume contraction but also value degradation through margin compression and product switching mechanisms.

## METHODS

### Data and sources

The primary data in this study consisted of monthly data on the volume (kg) and value (US$) of Balinese tuna exports from October 2016 to June 2023, sourced from the Bali Provincial Department of Industry and Trade (2024), covering all types of tuna products (fresh, frozen, and processed). Air logistics data, including international flight frequency and international passenger numbers at I Gusti Ngurah Rai Airport, were obtained from Angkasa Pura I and the Bali Provincial Statistics Agency (BPS) (2024). Sea logistics data, including the chronology of blank sailings and the suspension of container services at Benoa Port, were confirmed by reports from the Meratus Group (2020) and UNCTAD (2021).

This dataset was also used in Sitanggang *et al.* (2025) but was analyzed using a different approach. This study integrates STL, ARIMA, and Multiple Interrupted Time Series Analysis (MITSA) methods to analyze structural changes and vulnerabilities in the export logistics system.

Information regarding the Meratus Group's blank sailings is used as operational contextual evidence to support the interpretation of the results and is not used as the primary source of quantitative estimates in the model. Data on PSBB and PPKM policies were obtained from the National COVID-19 Task Force and BPS. Table 1 presents key data on Bali's logistics mode capacity across key policy phases as the empirical context for the analysis.

The Inactive status was intentionally retained because it represents a critical phase in Bali's logistics recovery. During this period, following the withdrawal of Meratus operator serving Bali's export routes, it had suspended its services due to insufficient cargo throughput. Consequently, direct sea freight services from Benoa Port were unavailable despite the gradual recovery of international air transportation. This condition highlights the asynchronous recovery between air and sea logistics modes, which forms an important context for interpreting the changes in export performance. Although Samudera subsequently introduced shipping services, these were later discontinued for the same operational reason, indicating that the recovery of maritime logistics remained incomplete throughout the study period. This asynchronous recovery between air and sea logistics supports the interpretation that improvements in flight connectivity did not immediately restore the overall performance of Bali's dual-mode export logistics system.

### Assumption testing and model diagnostics

Before model implementation, a series of diagnostic tests was conducted. (a) Stationarity Test: The Augmented Dickey-Fuller (ADF) test showed non-stationarity at the level for volume (t-stat = −2.14; p = 0.512) and export value, but both were stationary after the first differentiation (volume: t-stat = −6.83; p < 0.001; value: t-stat = −7.21; p < 0.001). (b) Autocorrelation Test: The Ljung-Box test on the residuals showed no significant autocorrelation at lags 1–12 (Q-stat = 14.23; p = 0.284 for volume; Q-stat = 11.87; p = 0.376 for value), confirming the residuals are white noise. (c) MITSA Model Validation: The model quality was evaluated using R-squared and Adjusted R-squared; Newey-West correction (bandwidth = 4) was applied to address residual autocorrelation and heteroscedasticity (Newey and West 1987). Multiple Interrupted Time Series Analysis (MITSA) was used to estimate changes in levels and trends due to six phases of policy intervention, referring to the interrupted time series approach for single and multiple interventions developed by Linden (2015). (d) ARIMA Model Selection: models were selected based on the smallest AIC and BIC criteria. Based on the AIC and BIC criteria, the best model for export volume is seasonal ARIMA (0,1,1)(0,1,1)[12], which shows a seasonal period of 12 months, which corresponds to the monthly data frequency in this study. The best model for export value is ARIMA (1,1,3).

### Additional regression: test of the influence of air mode capacity

A simple regression based on 15 international flight frequency data points for the 2019–2023 period was used to evaluate the relationship between belly cargo capacity and export performance. The model used is:

$$Value_t = \beta_0 + \beta_1 \times Flight_t + \varepsilon_t$$

Estimates are made using the Newey-West correction. Since full monthly time series of flight data are not available, the results of this analysis are indicative and should be used as supporting evidence, not as the primary conclusion of the study.

Table 1. Data on Bali's logistics mode capacity during critical phases of the pandemic.

| Phase/Period | Intl Flight/Month | Intl Passenger/Month | Δ vs. Baseline | Marine Modes Status |
|---|---|---|---|---|
| Pre-pandemic (June 2019) | 3,014 | 581,359 | — | Active |
| Large-Scale Social Restrictions (Apr–June 2020) | ~8–15 | ~8,000–15,000 | -99.7% | Pull-out (blank sailing) |
| Emergency PPKM (Jul–Aug 2021) | ~40 | ~45,000 | -98.7% | Inactive |
| Initial Recovery (June 2022) | 933 | 170,648 | -69.0% | Inactive |
| Advanced Recovery (Dec 2022) | 2,234 | 356,475 | -25.9% | Limited (Ocean) |
| Normalization (Apr 2023) | ~2,950 | 431,539 | -2.1% | Limited |

Sources: BPS Bali (2020; 2021; 2022; 2023; 2024); Meratus Group (2020); UNCTAD (2021). Δ = relative change to the June 2019 baseline (3,014 flights/month).

**Methodological limitations**

There are five main limitations: (1) The MITSA model assumes no major interventions other than those modeled, whereas changes in global commodity prices or extreme weather can affect exports simultaneously; (2) Available flight data at only 15 key points limits the statistical power of the regression; (3) Monthly data aggregation masks relevant weekly dynamics; (4) The positive level change in volume in the PSBB1 phase (+12.05 million kg; $p < 0.001$) is likely influenced by the extreme outlier of frontloading in April–May 2020, although robustness checks confirm the stability of the coefficient direction; and (5) The decline in global demand during the pandemic has the potential to affect export performance but cannot be empirically separated from the effects of domestic policies in this research design.

## RESULTS AND DISCUSSION

**STL decomposition results**

The STL analysis reveals a seasonal component consistent with two peaks per year: May–July (the optimal fishing season in the Southern Indian Ocean) and October–November (the pre-year-end global demand surge), consistent with Tuyu *et al.* (2023). The residual component identifies an outlier anomaly of >+3σ in April–May 2020 that is immediately followed by a sharp decline—a pattern consistent with frontloading before full restrictions take effect (Ivanov 2020). The trend component indicates structural stagnation that began in the third quarter of 2020 and did not show significant recovery until June 2023, as shown in Figure 1. Structural stagnation began to be evident in the third quarter of 2020.

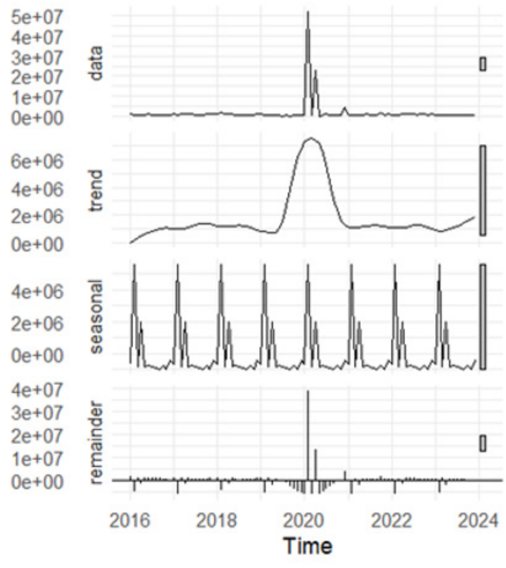


Figure 1. STL decomposition results of tuna export volume (kg) 2016–2023 (Bali Provincial Department of Industry and Trade 2024).

Figure 2 shows that the decline in export value was sharper than the change in export volume, indicating that logistical disruptions during the pandemic had a greater impact on the economic value aspect than the quantity of exports.

## ARIMA forecasting results

The Seasonal ARIMA (0,1,1)(0,1,1)[12] model for export volume projects a stable trend in the range of 1.0–1.2 million kg/month (July 2023–June 2026). The 95% confidence interval widens proportionally, with the lower limit reaching approximately 720,000 kg/month by the end of 2025. The ARIMA (1,1,3) model for export value projects a gradual downward trend from approximately USD 7.2 million to USD 6.8 million by June 2026. The projected decline in export value despite relatively stable export volume suggests continued pressure on unit export prices, consistent with higher logistics costs and a shift in product composition from fresh to frozen products during the pandemic (FAO 2022).

The projection results in Figure 3 show that export volumes tend to be stable in the medium period, indicating a gradual recovery, although they have not yet fully returned to pre-pandemic patterns.

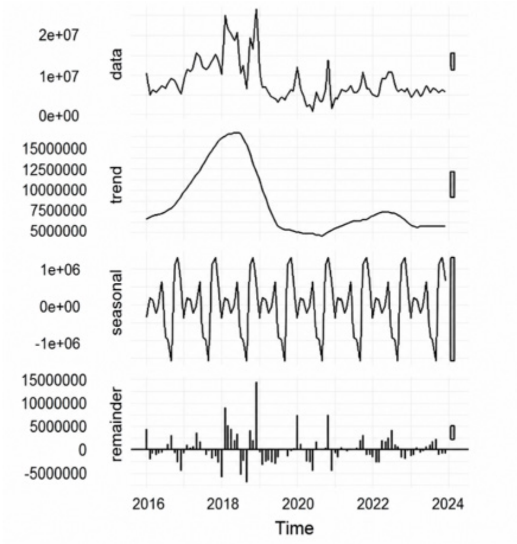


Figure 2. STL decomposition results of tuna export value (US$) 2016–2023 (Bali Provincial Department of Industry and Trade 2024).

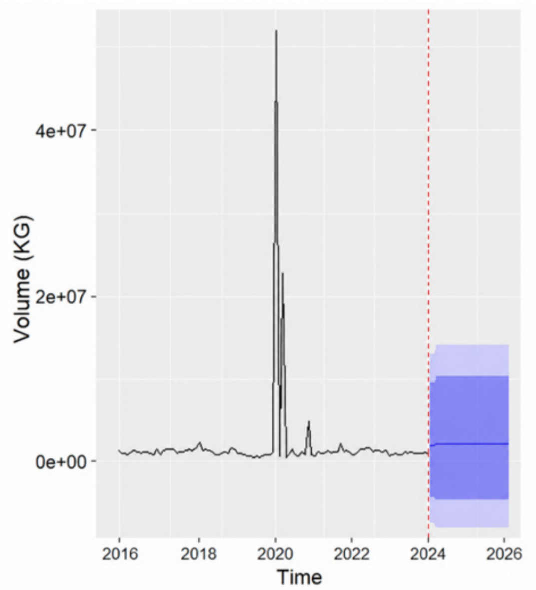


Figure 3. Forecasting Bali tuna export volume, July 2023–June 2026. Seasonal ARIMA (0,1,1) (0,1,1) model [12]*. Blue line = historical; orange line = projection; gray area = 95% CI (Bali Provincial Department of Industry and Trade 2024).

Figure 4 shows that the export value still shows a downward trend until the end of the projection period, which supports indications of medium-term structural vulnerability in the Bali tuna export logistics system.

**MITSA results: export volume**

Table 2 presents the MITSA regression coefficients for export volume. The model yields $R^2$ = 0.743 and adjusted $R^2$ = 0.689, explaining 74.3% of the variation in export volume. The Durbin-Watson test yields DW = 1.87, confirming the absence of serious autocorrelation in the residuals. The pre-pandemic trend is insignificant ($\beta_1$ = 106.338; p = 0.248), confirming stable conditions before the pandemic.

The implementation of PSBB1 resulted in a positive level change of +12,053,945 kg ($\beta_2$ = 12,053,945; 95% CI: +5,120,000, +18,987,890; p = 0.0006***). This figure needs to be interpreted with caution, as it is likely influenced by the extreme outlier of front-loading in April–May 2020. The subsequent slope change was -9,047,377 kg per month ($\beta_3$; p = 0.0004***), indicating a sharp decline in the trend after the initial surge, consistent with the paralysis of air logistics modes confirmed by blank sailings data. Level change ($\beta_2$) measures the shock effect—the immediate change when the intervention begins; slope change ($\beta_3$) measures the medium-term impact on the rate of change. In PSBB1, the combination of a positive level change with a negative slope change reflects a boom-bust cycle: a momentary surge (frontloading) followed by a sustained contraction. The pattern of changes in levels and trends due to policy interventions is clearly visible in Figure 5.

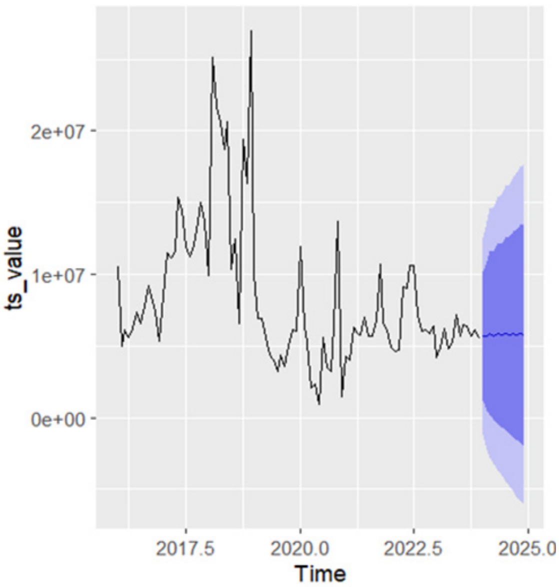


Figure 4. Forecasting Bali's tuna export value, July 2023–June 2026. ARIMA (1,1,3) model. Downward trend from ~USD 7.2 million to ~USD 6.8 million (Bali Provincial Department of Industry and Trade 2024).

Table 2. MITSA regression results for the impact of policy on Balinese tuna export volume (kg), Newey-West correction applied (*** p<0.001; ** p<0.01; * p<0.05; n.s. = not significant. $R^2$ = 0.743; Adj $R^2$ = 0.689; DW = 1.87).

| Intervention | Level Change ($\beta_2$) | p-value | Slope Change ($\beta_3$) | p-value | Sig. |
|---|---|---|---|---|---|
| PSBB1 (Apr–Jun 2020) | +12,053,945 kg | 0.00056 | −9,047,377 kg | 0.00038 | *** |
| PSBB2 (Jul–Dec 2020) | +21,082,681 kg | 0.00176 | +9,882,713 kg | 0.00023 | ** |
| PPKM1 (Jan–Jun 2021) | +15,716,510 kg | 0.02806 | −369,678 kg | 0.53015 | * |
| PPKM2 (Jul–Agt 2021) | +11,033,073 kg | 0.02495 | +4,840,209 kg | 0.19495 | * |
| PPKM3 (Sep 2021–Feb 2022) | +2,230,428 kg | 0.36525 | −5,098,638 kg | 0.18102 | n.s. |
| PPKM4 (Mar 2022–Jun 2023) | +750,182 kg | 0.44717 | −279,205 kg | 0.37496 | n.s. |

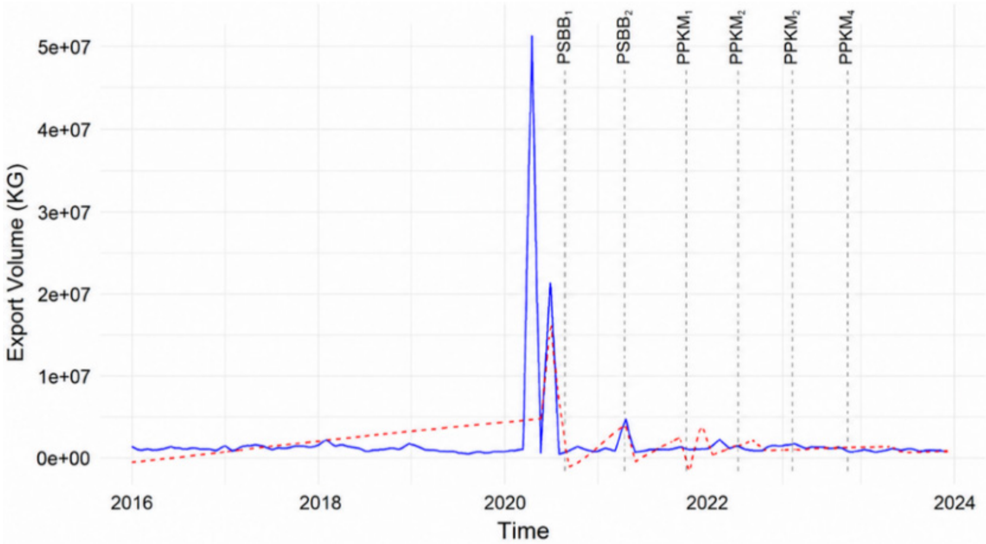


Figure 5. Multiple interrupted time series analysis of Bali's tuna export volume, 2016–2023. Blue line = actual; dashed red line = counterfactual without intervention; vertical line = policy interruption point (Bali Provincial Department of Industry and Trade 2024).

**MITSA results: export value**

Table 3 presents the MITSA coefficient for export value. The model produces $R^2 = 0.681$ and an adjusted $R^2 = 0.618$. The Durbin-Watson test yielded DW = 1.93, confirming the absence of serious autocorrelation. The pre-pandemic trend is not significant (p = 0.452), indicating market stability before the pandemic.

PSBB1 caused a very significant decline in export value of -USD 7,718,352 ($\beta_2$ = -7,718,352; p = 0.0000829***), without a significant slope change ($\beta_3$ = -507,725; p = 0.6198). This initial shock was a one-time but destructive one: the loss of belly cargo access directly eroded the value per kilogram of exported products. The emergency PPKM phase (PPKM2) showed a decline of -USD 8,578,704 (p = 0.122, not statistically significant), but the magnitude was substantial. In the PPKM3 phase, a significant decline of -USD 5,980,235 (p = 0.0265*) was found. Visual inspection of Figure 6 indicates a downward trend in export value during the Emergency PPKM period, although the corresponding MITSA coefficients for PPKM2 (slope change: -USD 333,287; p = 0.877) are not statistically significant. This pattern is consistent with sustained economic pressure on export value extending beyond the immediate policy shock and should be interpreted as a graphical observation rather than a formally estimated coefficient. Sitanggang *et al.* (2025) confirmed that belly cargo capacity is the most critical component in Bali's fresh tuna logistics system, with delivery time (weighted at 0.349) and reliability (0.331) being the dominant criteria in expert assessments. Figure 6 shows the pressure on export value that continues after the Emergency PPKM phase.

Table 3. MITSA regression results for the impact of policy on Balinese tuna export value (USD), Newey-West correction applied (*** p<0.001; * p<0.05; n.s. = not significant. $R^2 = 0.681$; Adj $R^2 = 0.618$; DW = 1.93).

| Intervention | Level Change ($\beta_2$) | p-value | Slope Change ($\beta_3$) | p-value | Sig. |
|---|---|---|---|---|---|
| PSBB1 (Apr–Jun 2020) | −USD 7,718,352 | 0.0000829 | −USD 507,725 | 0.6198 | *** |
| PSBB2 (Jul–Dec 2020) | −USD 3,784,796 | 0.1651 | +USD 914,447 | 0.7026 | n.s. |
| PPKM1 (Jan–Jun 2021) | −USD 6,630,901 | 0.3367 | +USD 168,206 | 0.9219 | n.s. |
| PPKM2 (Jul–Agt 2021) | −USD 8,578,704 | 0.1219 | −USD 333,287 | 0.8769 | n.s. |
| PPKM3 (Sep 2021–Feb 2022) | −USD 5,980,235 | 0.0265 | −USD 1,008,883 | 0.6766 | * |
| PPKM4 (Mar 2022–Jun 2023) | −USD 1,552,404 | 0.2210 | +USD 571,532 | 0.3535 | n.s. |

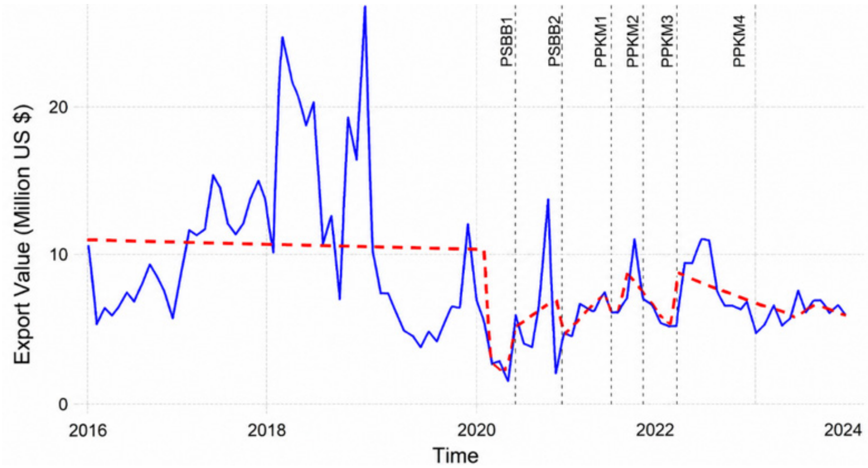


Figure 6. Multiple Interrupted Time Series Analysis of Bali's tuna export value from 2016 to 2023. The sharp decline in April 2020 ($\beta_2$ = -USD 7.72 million; p<0.001) and the slope change during the Emergency and the sustained downward trend in export value during the Emergency PPKM period are clearly visible (Bali Provincial Department of Industry and Trade 2024).

**Regression results of the influence of air mode capacity**

Table 4 presents the regression results of the effect of international flight frequency on export performance (n = 15 key data points, 2019–2023). Given the limited number of passengers, these results are indicative.

Pearson correlations confirmed a very strong relationship between flight frequency and export value ($r = 0.923$; $p < 0.001$) and a strong relationship with volume ($r = 0.858$; $p < 0.001$). The higher correlation strength for value compared to volume quantitatively strengthens the argument that belly cargo is more a determinant of export value quality than simply quantity. Robustness checks by removing three extreme outlier-collapsing observations yielded a coefficient of $\beta_1$ = USD 1,498 per flight ($p < 0.001$; $R^2 = 0.926$), smaller than the full model but still significant and in the same direction, confirming that the Model 1 results are not an outlier artifact.

**Discussion: volume-value divergence mechanism**

One of the most crucial findings is the divergence observed during the Emergency PPKM period (July–August 2021). Although the MITSA model did not identify statistically significant changes in export value level or slope coefficients during PPKM2, visual inspection of Figure 6 indicates a sustained downward pattern throughout this period. This graphical pattern is consistent with continued economic pressure within the export supply chain. This divergence indicates that export quantity was maintained, whereas its economic value showed a persistent downward pattern, reflecting increasing pressure within the export supply chain (Sitanggang *et al.* 2025). Flight capacity data for the same period (approximately 40 flights/month compared with 3,014 flights before the pandemic) provide supporting evidence for this interpretation. The value-to-volume ratio (USD/kg) also shows a persistent decline in the average export value per kilogram of tuna, particularly during the period of stricter mobility restrictions. As shown in Figure 7, the value-to-volume ratio has continued to decline since 2020.

The economic mechanisms underlying the observed divergence can be interpreted using Transaction Cost Economics (TCE) (Williamson 1985). During the PPKM period, exporters faced higher logistics-related transaction costs associated with disruptions to transportation and supply chain coordination. International sea freight rates also increased substantially because of supply-demand imbalances and container shortages during the COVID-19 pandemic (USITC 2021), further increasing logistics costs. In the context of Bali, these additional costs included transporting empty refrigerated containers from Surabaya to Bali, ferry transportation, returning containers to Tanjung Perak, additional cargo handling, longer transit times, and extended cold-chain operations. These additional costs were largely borne by exporters while export prices remained highly competitive, contributing to lower export values despite relatively stable export volumes. Second, product switching from fresh to frozen: belly cargo is a vital channel for fresh tuna (shelf life <5 days), so the collapse of flights has encouraged a shift to frozen products with lower value per kg; slower land-sea routes inherently support this shift (Love *et al.* 2021). Third, cold chain quality degradation: multiple handling on alternative routes increases the risk of temperature fluctuations and reduces the final product quality (FAO 2022).

This shift in product mix tends to persist throughout the observation period until December 2022. Although flights have recovered to 2,234 flights per month, export values have not yet returned to pre-pandemic levels. With data ending in June 2023, these findings indicate a medium-term structural shift consistent with the new normal, at a lower level than the pre-pandemic period.

### Confirmation of marine mode disruption

The disruption of maritime transport was confirmed by the decision of Meratus Line, the main feeder shipping operator on the Benoa–Surabaya route, to cease services (blank sailings) in April 2020 due to a commercially unviable decline in load factors (Meratus Group 2020). Blank sailings are a common strategy for global shipping operators to maintain network efficiency amidst declining demand (UNCTAD 2021). As a result, frozen tuna exporters lost direct access to refrigerated container services from Benoa Port, forcing the adoption of a multimodal route via Surabaya as a cost-intensive lifeline. Samudera Indonesia's initiative to open an export route from Bali in July 2022 provided positive signals, but services ceased again in late 2022 due to low load factors, confirming a deeper structural weakness: Bali's tuna export volumes were insufficient to sustain direct shipping services commercially.

### Theoretical and policy implications

The findings of this study reinforce and extend Ivanov's (2020) concept of the ripple effect in a specific context: dual-mode perishable supply chains in developing countries. Unlike manufacturing supply chains, which have buffer inventory and more flexible mode substitution, fresh tuna logistics is highly time-critical and mode-dependent, making disruptions to one mode uncompensated without significant value degradation costs. From a supply chain resilience perspective, Ivanov and Dolgui (2022) distinguish between reactive adaptive capabilities and proactive recovery capabilities in supply chain resilience. The findings of this study indicate that Balinese tuna export logistics successfully implemented reactive adaptation (switching to multimodal), but failed to achieve a bounce-back to pre-pandemic value levels within the observation period, leading to a structural lock-in where emergency adaptation tends to persist.

Policy implications cover two dimensions. From a national logistics perspective, policies are needed that encourage planned, rather than reactive, mode diversification, including the development of dedicated freighters for fresh fishery commodities and increased cold storage capacity at major export ports. From an industry perspective, exporters need to implement a mixed product portfolio strategy that actively manages the fresh-frozen mix based on the availability of logistics modes, not solely on market demand.

## CONCLUSION

This study shows that PSBB and PPKM policies are associated with significant changes in Bali's tuna export logistics system, primarily through declining export value and disruptions to transportation capacity. Belly cargo capacity is strongly correlated with export performance, while the divergence between relatively stable volumes and declining values indicates margin compression, a shift from fresh to frozen tuna, and pressure on the cold chain system. ARIMA projections indicate that although export volumes tend to stabilize, the recovery in export value will remain slow through the medium term. These findings indicate medium-term structural vulnerabilities in Bali's dual-modal tuna export logistics system, necessitating a more proactive, adaptive, and data-driven logistics policy to enhance the competitiveness of Indonesian fisheries exports.

Table 4. Regression results of the effect of international flight frequency on export performance (n = 15 data points, 2019–2023), Newey-West correction applied, *** p < 0.001.

| Model | Coefficient $\beta_1$ | p-value | $R^2$ | Adj $R^2$ |
|---|---|---|---|---|
| *Value* = $\beta_0 + \beta_1 \times$ *Flight* | USD 1,914/flight | 0.000001*** | 0.853 | 0.841 |
| *Volume* = $\beta_0 + \beta_1 \times$ *Flight* | 272.8 kg/flight | 0.000043*** | 0.736 | 0.715 |
| Robustness (excluding 3 obs outlier) | USD 1,498/flight | 0.000002*** | 0.926 | 0.918 |

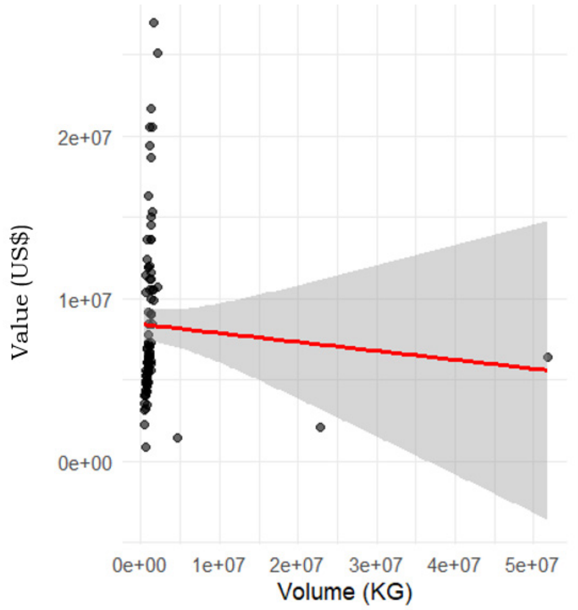


Figure 7. Value-to-volume ratio (USD/kg) of Bali tuna exports, 2016–2023. The figure indicates a sustained decline in export value per kilogram since 2020, consistent with increasing economic pressure on tuna exports (Bali Provincial Department of Industry and Trade 2024).

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