Saintek Perikanan: Indonesian Journal of Fisheries Science and Technology
Available at http://ejournal.undip.ac.id/index.php/saintek
Vol. 22 No. 2 : 153 - 159, August 2026

DYNAMICS OF *Sardinella lemuru* IN THE BALI STRAIT: ANALYSIS OF FLUCTUATIONS AND SUSTAINABILITY FROM 2014 TO 2024

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ABSTRACT

Sardinella lemuru was an important fishery commodity in the Bali Strait, with significant production fluctuations. This study aims to analyze the production dynamics of *Sardinella lemuru* for the period 2014–2024 and identify the factors influencing them. The research method employed quantitative descriptive analysis and temporal trend analysis of production data from the Pengambengan Fisheries Research Station (PPN) and the Muncar Fisheries Research Station (PPP). The results indicate that *Sardinella lemuru* production is highly fluctuating, exhibiting a cyclical pattern every 2–3 years. The 2017–2018 period was the lowest in the past 11 years, with production not exceeding 300 tons per month. This collapse was influenced by overfishing during the 2014–2017 period, as evidenced by the declining CPUE trend. Other factors affecting production fluctuations include the biological cycle of *Sardinella lemuru*, seasonal migration patterns, and changes in oceanographic conditions. A significant increase in production began in 2020–2024, indicating a recovery of stock following the collapse period. This study suggests the need for sustainable management through the implementation of a quota system and improved gear selectivity.

Keywords: *Sardinella lemuru*; Production Fluctuations; CPUE; Sustainability; Bali Strait

INTRODUCTION

The Bali Strait, located between the islands of Bali and Java, is a critically important marine area for Indonesia's marine ecosystems and fisheries, boasting the greatest potential for pelagic fish catches, including *Sardinella lemuru* (Setyohadi *et al*., 2009). The waters of this strait are part of the Republic of Indonesia's Fisheries Management Area 573 (WPPNRI 573), known for the complexity of its oceanographic dynamics due to the influence of various factors, such as ocean currents, sea surface temperature, salinity, and upwelling phenomena (Wijaya, 2021). Upwelling brings nutrient-rich water from the lower layers, resulting from the decomposition of organic matter up into the photic zone, thereby enabling photosynthesis and triggering the growth of phytoplankton populations as primary producers (Cushing, 1971; Pauly & Christensen, 1995; Nybakken & Bertness, 2005). These conditions attract zooplankton and small fish, such as the Lemuru fish, as subsequent consumers. Additionally, these oceanographic dynamics influence feeding grounds and the distribution of fish schools, particularly among species sensitive to temperature changes (Ningsih *et al*., 2018).

Sardinella lemuru is a fishery commodity of significant economic value to coastal communities around the Bali Strait (Sihombing *et al*., 2017). *Sardinella lemuru* fishing has become the primary activity sustaining the livelihoods of fishermen in two regencies: Jembrana (Bali Province) and Banyuwangi (East Java Province). *Sardinella lemuru* production in this region has unique characteristics, with highly dynamic fluctuations over time. Over the past few decades, *Sardinella lemuru* fishery in the Bali Strait has experienced several episodes of collapse and recovery. These collapse events are marked by a dramatic disappearance of *Sardinella lemuru* from fishing grounds, as occurred in 1999 and 2011 (Nugraha *et al*., 2018). This situation creates economic uncertainty for fishermen and the fish processing industry that rely on *Sardinella lemuru* availability.

A deep understanding of the patterns of lemur production fluctuations is crucial as the foundation for sustainable fisheries management. Several previous studies have attempted to analyze the factors influencing *Sardinella lemuru* abundance in the Bali Strait. However, these have been limited to specific periods and have not examined long-term patterns encompassing multiple collapse and recovery cycles, including the absence of *Sardinella lemuru* catches in 2014, 2017, and 2018. This study aims to analyze the dynamics of *Sardinella lemuru* production in the Bali Strait over 11 years (2014–2024), identify the factors influencing production fluctuations, and formulate recommendations for sustainable management of *Sardinella lemuru* fisheries. The research results are expected to serve as a scientific basis for policy-making regarding *Sardinella lemuru* fisheries management in the Bali Strait that integrates ecological aspects.

RESEARCH METHODOLOGY

This study was conducted at PPN Pengambengan (Jembrana) and PPP Muncar (Banyuwangi) from August to December 2024. The selection of these locations was based on the strategic positions of the two ports, which are situated on opposite sides of the Bali Strait and serve as the main landing centers for *Sardinella lemuru* (Figure 1). The data used consisted of monthly time series data from January 2014 to December 2024, covering production volume (tonnage) and fishing effort (trips). Data from both ports were compiled (combined) to

Received: 18-06-2025, Last Revised: 07-03-2026, Accepted: 09-03-2026, Available Online 10-06-2026, Published: 12-06-2026

represent the total production and fishing effort of *Sardinella lemuru* stock in the Bali Strait. This data integration approach refers to previous research by Setyohadi (2009) and Wijaya (2021), which states that *Sardinella lemuru* population in these waters constitutes a *single stock* that migrates spatially within the Bali Strait region; therefore, landing data from both sides of the strait must be analyzed in an integrated manner. All data were obtained from official statistical reports issued by the relevant fisheries port authorities.

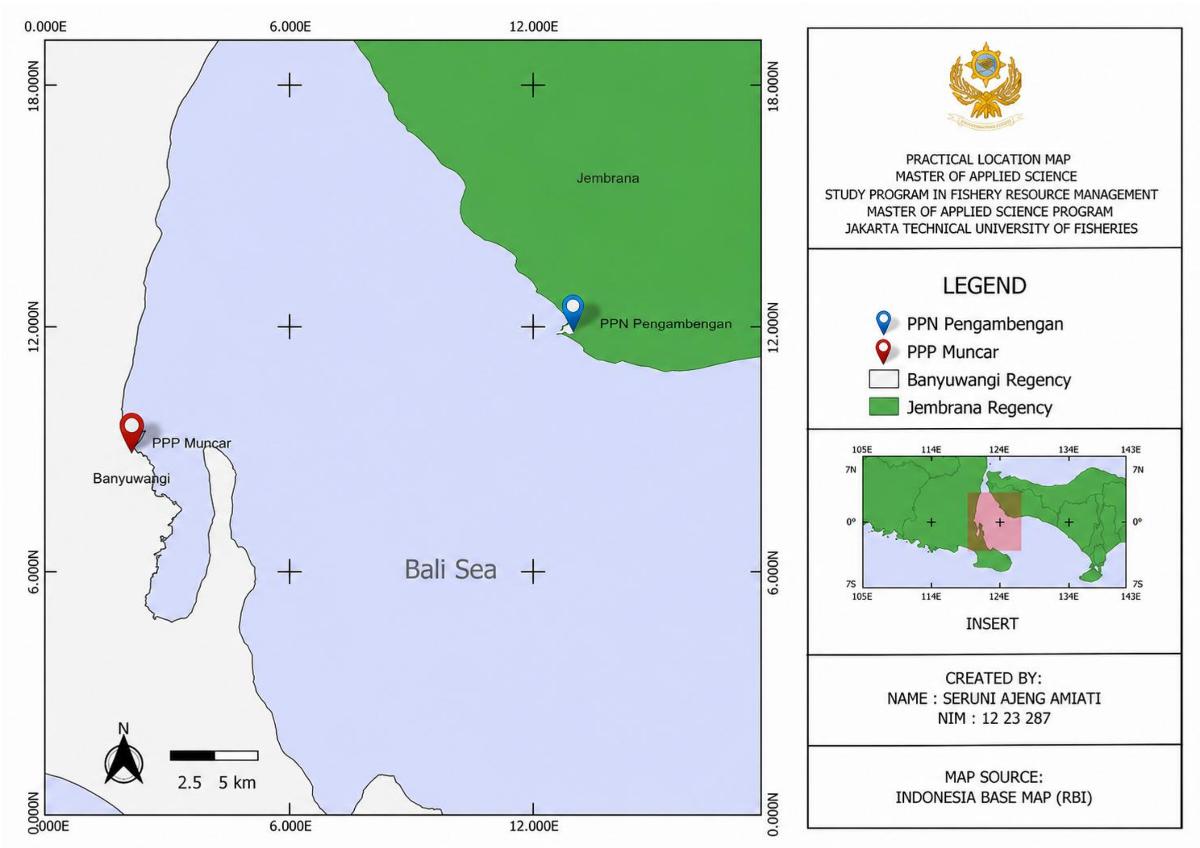

Figure 1. Research Location

Data Types and Sources

This study employs a quantitative descriptive approach using secondary time-series data. The primary data used include monthly and annual production data for *Sardinella lemuru* as well as landing effort data from the Nusantara Fishing Port (PPN) in Pengambengan, Jembrana Regency, and the Muncar Coastal Fishing Port (PPP) in Banyuwangi Regency. The analyzed data cover 11 years, from January 2014 to December 2024, sourced from the official statistical reports of the two fisheries ports.

Determination of Fishing Effort Units

The fishing effort unit is determined based on the number of fishing trips per month. To ensure data consistency, effort was standardized by designating the purse seine as the standard fishing gear. This selection is based on the dominance of the Purse Seine in catching lemuru in the Bali Strait, where other fishing gear is converted to minimize bias in the calculation of Catch Per Unit Effort (CPUE).

Stock Abundance Analysis (CPUE)

The abundance of lemuru fish stocks was analyzed using the Catch Per Unit Effort (CPUE) indicator. The CPUE value was calculated by dividing the total catch by the standardized fishing effort for a single purse seine trip. This analysis was used to identify trends in fluctuations in fish abundance over time and to detect signs of overfishing.

$$CPUE_t = \frac{C_t}{f_t} \qquad \text{.. (1)}$$

Note: $CPUE_t$ = Catch per unit of effort in period t (kg/trip or tons/trip); Ct = Total catch of lemuru fish during period t (kg or tons); f_t = Total fishing effort (*Purse Seine* trips) during period t

Analysis of Seasonal Variations and Temporal Trends

A temporal trend analysis was conducted to identify annual and monthly patterns of Lemuru production fluctuations for the period 2014–2024. This method employs descriptive trend analysis and *the Moving Average* to smooth out short-term fluctuations, thereby enabling the identification of stock depletion cycles (Setyohadi, 2009). Based on the data, seasonal patterns in the Bali Strait indicate a peak season from September to January, with the off-season from April to July.

The use of a moving average helps identify the collapse phase in 2017–2018 and the post-2020 recovery phase. The identified 2–3-year cyclical pattern is consistent with the findings (Sambah *et al*., 2021) stating that *Sardinella lemuru* stock dynamics are highly sensitive to temporal environmental changes. This analysis is crucial for distinguishing between production declines caused by seasonal factors and those caused by overfishing (Nugraha *et al*., 2018).

Analysis of the Relationship Between Fishing Effort and Productivity (Regression)

A simple linear regression analysis was used to test the effect of fishing effort on productivity (CPUE); the model is based on Walpole (1995).

$$Y = a + b.x \quad \text{.. (2)}$$

Notes: Y = CPUE (*Catch Per Unit Effort*); a = Intercept
b = *Slope* of the trend line; x = *Effort*

This analysis examines the extent to which changes in the number of trips affect the catch rate. If the value of b is negative and significant, this indicates that the increase in fishing effort has exceeded the stock's recovery capacity, suggesting the occurrence of overfishing in the waters of the Bali Strait (Setyohadi, 2009; Wijaya, 2021).

RESULTS AND DISCUSSION

Lemuru Fish Catch in the Bali Strait

Sardinella lemuru fishing activities in the Bali Strait are primarily conducted by fishermen from Banyuwangi and Jembrana Regencies, with purse seine (pukat cincin) being the dominant fishing gear used in the fishery. Other fishing gears operated in the region include gillnets, surface danish seine, stationary lift net, and beach seines, which collectively support the exploitation of *Sardinella lemuru* resources in the Bali Strait (Mainnah *et al*., 2023). Among these types, the purse seine is the most widely used fishing gear. This is due to its operational effectiveness in exploiting small pelagic fish such as *Sardinella lemuru*, which live in schools. In addition to being able to catch large volumes in a single operation, the purse seine offers higher catch productivity and better economic efficiency compared to other fishing gears. The dominance of purse seine use on both sides of the Bali Strait reinforces the relevance of selecting this fishing gear as the standard unit in the analysis of fishing effort in this study.

Fishing operations in Muncar and Pengambengan utilize a two-vessel system equipped with purse seine units. Based on field observations and port technical data, the mesh size used during the 2014–2024 period was 0.75 inches. Although effective at maximizing catch volume, this mesh size is considered non-selective because it captures fish below the minimum legal size (Ip *et al*., 2023). This is confirmed by the 2017 PPP Muncar data, which show that 74% of the catch measured <17.3 cm, far below the gonadal maturity standard of 18.9 cm (Putra *et al*., 2020). This condition is strongly suspected to disrupt the reproductive cycle of *Sardinella lemuru* stock by capturing juvenile individuals before they have a chance to spawn.

Efforts to improve fishing gear design have been recommended through studies(Mainnah *et al*., 2023), confirming that the use of a 1.5-inch mesh size in accordance with Ministry of Marine Affairs and Fisheries Regulation No. 59 of 2020 can improve catch selectivity, with an ideal mesh opening (MO) of 3.3 cm to ensure that *Sardinella lemuru* reach marketable size. Therefore, this recommendation is highly relevant to our research findings, which show that lemuru fishing practices in the Bali Strait during the 2014–2017 period were characterized by a decline in CPUE and an increase in the proportion of small-sized fish in the catch. These conditions indicate high exploitation pressure and contributed to the population collapse phase in 2017–2018. These findings underscore that improving the selectivity of fishing gear is a critical step toward more efficient resource use and preventing the recurrence of extreme production fluctuations.

The Life Cycle and Migration Patterns of Lemurs

One of the biological characteristics of *Sardinella lemuru* that influences fluctuations in catch yields is the time required for stock recovery. *Sardinella lemuru* require approximately 2–3 years to recover their stocks after intensive exploitation (Listiani & Wijayanto, 2016). This explains why periods of high catch are typically followed by several years of declining catch yields, as occurred in 2017–2018. Seasonal migration patterns also significantly influence the availability of *Sardinella lemuru* in fishing areas. *Sardinella lemuru* in the waters of the Bali Strait are known as seasonal fish because they appear only during specific seasons. Research by Daduk *et al*. (2021) indicates that *Sardinella lemuru* catches during the west monsoon season are far greater than during the east monsoon season, which often experiences upwelling phenomena even though the number of fishing trips is lower during the west monsoon. This suggests that the magnitude of lemuru catches is not solely determined by upwelling, but also by the behavioral dynamics of the fish and water conditions that influence the effectiveness of fishing operations. During the eastern season, increased productivity due to upwelling does not always correlate directly with catch yields because of changes in schooling structure or less favorable oceanographic conditions that hinder fishing activities. Conversely, the western season often offers better water stability, enabling fishing operations to proceed more effectively. This indicates that catch fluctuations result from interactions among environmental factors, biological behavior, and fishermen's ability to access fishing grounds.

Sardinella lemuru exhibit seasonal migratory behavior, disappearing from fishing grounds at certain times (Setyohadi *et al.,* 2018). This phenomenon occurs primarily during the final months of the east monsoon season. This migratory behavior is linked to the lemur's life cycle and food availability in the waters. A study by Panjaitan (2009) revealed the presence of fairly large schools of *Sardinella lemuru* at depths of 40–80 m, 20–70 m, and 50 m in the waters of the Bali Strait. This indicates that lemurs tend to school in the euphotic zone, which is rich in nutrients, during certain seasons. The schooling pattern at depths of 40–80 m indicates that during certain periods, particularly the end of the east monsoon season, *Sardinella lemuru* schools may be located in layers approaching or exceeding the operational limits of fishing gear, which is generally effective up to around 70 m. Consequently, part of the population becomes inaccessible to fishermen, creating the impression that *Sardinella lemuru* have disappeared from the fishing area.

Variations in the abundance of *Sardinella lemuru* in a given body of water are influenced by the migration patterns of *Sardinella lemuru* fish themselves. The most relevant migration pattern in the Bali Strait is the local migration from deep to shallow waters during the East Monsoon, when upwelling triggers increased water productivity (Putra, 2016; Pratama *et al*., 2022). During this period, *Sardinella lemuru* enter shallow waters to feed and begin spawning, consistent with findings regarding increased population density at the end of the East Monsoon season (Panjaitan, 2009). However, CPUE data from 2014–2024 indicate that CPUE was higher in some years during the West Monsoon, reflecting more stable sea conditions and improved fishing efficiency (Setyohadi *et al*., 2018). Thus, the difference between the biological appearance of the lemuru and the peak catch is primarily influenced by oceanographic factors and the intensity of fishing operations.

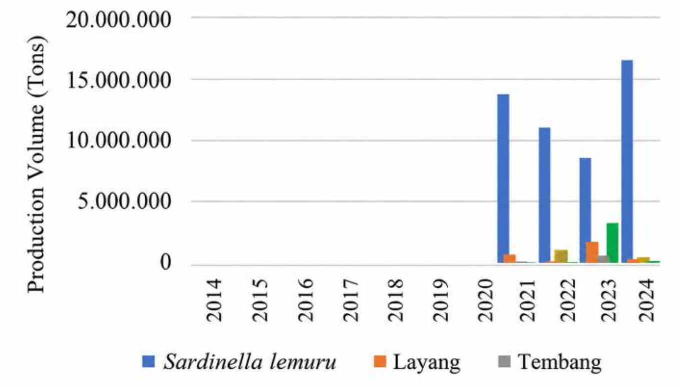

Figure 2. Catch Composition 2014–2024

Fluctuations in Lemuru Production from 2014 to 2024

Based on an analysis of *Sardinella lemuru* production data landed at PPN Pengambengan and PPP Muncar from January 2014 to December 2024, a highly dynamic fluctuation pattern was identified over the 11-year observation period (Figure 3). These fluctuations exhibit cyclical characteristics with specific periods consistent with the biological and ecological nature of *Sardinella lemuru*.

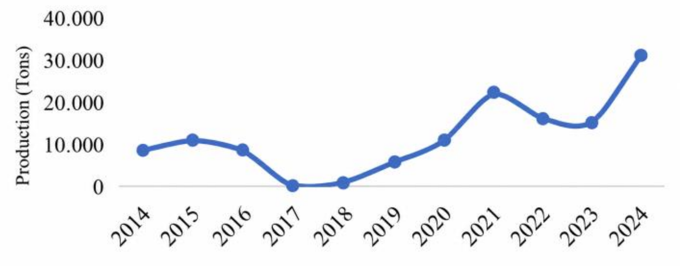

Figure 3. *Sardinella lemuru* Production, 2014–2024

Analysis of production data for the 2014–2024 period reveals a cyclical fluctuation pattern divided into three main phases: the high-production phase (2014–2016), the collapse phase (2017–2019), and the recovery phase (2020–2024). The collapse phase was marked by a drastic decline in production from 10,000 tons (2014) to 1,000–2,000 tons (2017–2018), coinciding with low CPUE values due to biological overfishing pressure in previous years.

Entering the third phase, production surged significantly, peaking at 30,000 tons in 2024. This major surge is identified as a massive stock recovery phase, given that the increase in production runs parallel to an increase in CPUE (Figure 4), rather than being solely due to a massive expansion of the fishing fleet as depicted in Figure 3. This indicates that the environmental carrying capacity and natural recruitment of *Sardinella lemuru* stock in the Bali Strait have returned to optimal levels following the collapse period, resulting in a drastic increase in catch efficiency per unit of effort (Sambah *et al.*, 2021; Wijaya, 2021).

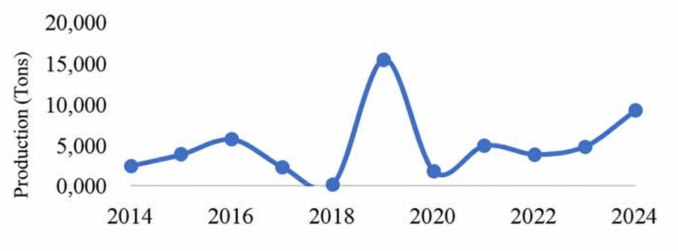

Figure 4. *Sardinella lemuru* CPUE, 2014–2024

Production Decline Phase (Collapse Phase)

The 2017–2018 period marked the lowest phase of *Sardinella lemuru* production during the eleven-year observation period, characterized by near-zero monthly production, as in February 2017, when no catches were recorded. This pattern is not a new phenomenon, as historical data indicate that lemurs in the Bali Strait also experienced collapse phases in 19, 1999, 2011 (Jatisworo *et al*., 2022). Similar findings were reported by Adhihapsari *et al*. (2024) at the Prigi Fisheries Monitoring Station, indicating that the 2016–2018 period represented a phase of sharp decline in lemuru production, with the lowest point occurring in 2017. The consistency of this pattern across two locations indicates that extreme fluctuations are an inherent characteristic of *Sardinella lemuru* fisheries in the waters south of Java to the Bali Strait, further complicating predictions regarding the location and timing of stock appearances.

The collapse of *Sardinella lemuru* production in 2017–2018 was caused by a combination of several interrelated factors. High fishing pressure in the preceding period prevented the stock from recovering, as reflected by a decline in CPUE and the dominance of small-sized fish in the catch—a classic indicator of growth overfishing, where fish stocks are not allowed to grow and spawn optimally before being caught (Setyohadi *et al*., 2021; Sambah *et al*., 2021). At the same time, oceanographic conditions in the Bali Strait further exacerbated the situation, particularly due to global climate anomalies such as El Niño (Figure 5), which increased surface temperatures and reduced water fertility. These conditions reduce the availability of plankton as the primary food source for *Sardinella lemuru*, thereby suppressing primary productivity. The weakening of the upwelling system during this period also reduces nutrient availability in the euphotic zone, preventing optimal aggregation of *Sardinella lemuru* in shallow waters.

Biological population factors further exacerbated this collapse. *Sardinella lemuru* have a short lifespan with a population recovery cycle of approximately 2–3 years, so the period of high exploitation in 2014–2016 directly led to a drastic decline in stocks in 2017–2018. Several studies in southern Java and the Bali Strait also report the same pattern—very low production in 2016–2018 and increasingly difficult-to-predict fishing locations (Jatisworo *et al*., 2022; Adhihapsari *et al*., 2024). Thus, the 2017–2018 collapse phase resulted from the interaction between fishing pressure, oceanographic anomalies, and unstable population dynamics, rather than a single factor. An analysis of the overlay graph of *Sardinella lemuru* production against the ENSO index (ONI) and DMI from 2014 to 2018 reveals a strong correlation between regional climate anomalies and the dynamics of declining production, culminating in the collapse phase of 2017–2018. During the 2014–2016 period, ONI values were in the positive phase, indicating moderate to strong El Niño episodes, while DMI values tended to be negative to neutral. These conditions indicate a weakening of upwelling in the waters south of Java, including the Bali Strait, due to rising sea surface temperatures and a reduced supply of nutrients from the lower layers. The impact was evident in *Sardinella lemuru* production, which began to decline in 2015 and continued to drop, reaching very low levels in 2016.

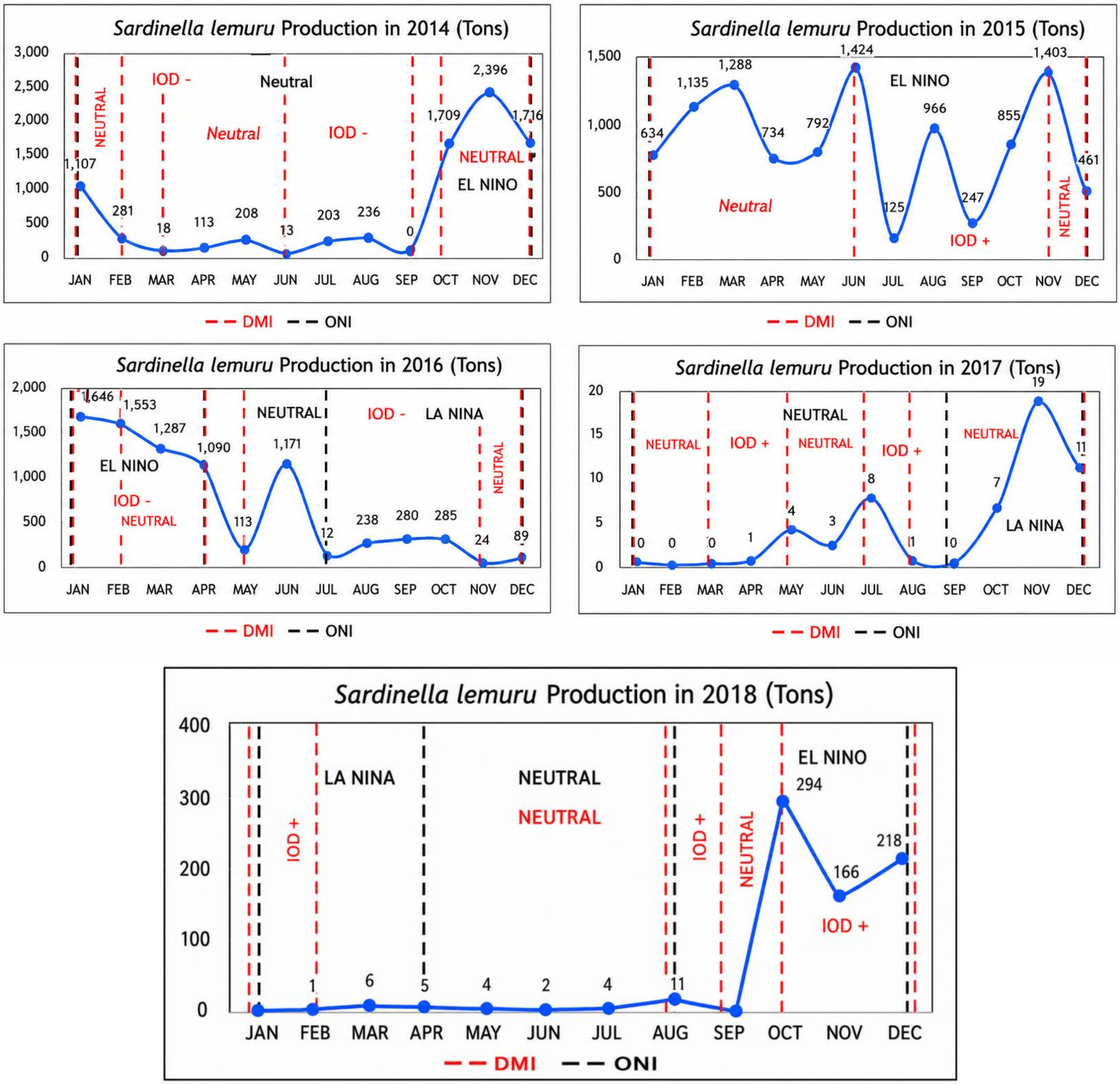

Figure. 5 Overlay of Lemuru Production with ENSO and DMI 2014–2018 (Collapse Phenomenon)

As of 2017, ENSO has once again entered a weak positive phase, while the DMI continues to show no signs of significant nutrient enrichment. The combination of a positive ONI and a weak DMI indicates that the waters of the Bali Strait remain in a less productive state, keeping plankton biomass—*Sardinella lemuru* primary food source—at low levels. This situation further impairs *Sardinella lemuru* population's ability to recover from the fishing pressure of the previous period. This is reflected in the 2017 catch, which fell to its lowest point, including months with no catch at all.

In 2018, although ENSO conditions began to shift toward a neutral phase, upwelling intensity had not yet fully recovered. DMI also showed variations that were not strong enough to trigger an increase in primary productivity. As a result, the recovery of populations dependent on high productivity during the eastern season was not optimal. *Sardinella lemuru* production from January to September 2018 remained at very low levels before gradually showing signs of recovery heading into 2019. Thus, the 2014–2018 graph overlay confirms that the combination of fishing pressure and unfavorable oceanographic conditions—marked by the dominance of positive ENSO and weak DMI was the primary factor triggering the lemur population collapse in 2017–2018, underscoring that regional climate anomalies played a major role in causing the decline in *Sardinella lemuru* abundance during that period.

Seasonal Variations and Abundance (CPUE) of *Sardinella lemuru*

The CPUE graph from this study (Figure 4) shows a clear downward trend during 2014–2017, indicating a decline in lemuru abundance despite no significant increase in fishing effort. This pattern is reinforced by the decreasing size of caught fish and a shift in fishing operations to more distant waters, which are common indicators of overfishing. The RAPFISH sustainability assessment by Putri *et al.* (2023), which classified the Bali Strait lemuru fishery as 'unsustainable,' reinforces that anthropogenic pressures during that period also contributed to the decline in stock condition.

Overlaying production data with ENSO and DMI indices indicates that the 2014–2016 El Niño episode and weak upwelling reduced primary productivity in the Bali Strait. Extreme temperature variations in 2017–2018 caused the lemuru to move to depths beyond the reach of fishing gear, resulting in a further decline in CPUE and production, which reached its lowest point. Thus, the decline in CPUE and the collapse of the lemuru population in 2017–2018 were the combined result of high fishing pressure and unfavorable oceanographic conditions.

Regression and Correlation Analysis of Lemuru Fisheries

The results of the statistical analysis show a coefficient of determination (R^2) of 0.23, indicating that the fishing effort variable can explain 23% of the variation in CPUE. This figure suggests that the influence of fishing intensity on fluctuations in stock abundance is relatively low. Conversely, 77% of the variation in *Sardinella lemuru* abundance is influenced by factors outside the model, such as oceanographic dynamics and climate change (Sambah *et al*., 2021). The low value of the coefficient of determination provides empirical evidence that the presence of *Sardinella lemuru* stocks in the Bali Strait is more strongly influenced by environmental factors than by human activities (fishing), consistent with Wijaya's (2021) findings.

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.487[a]	.238	.153	3.88306	1.676

a. Predictors: (Constant), Effort (Trip)

b. Dependent Variable: CPUE (Ton/Trip)

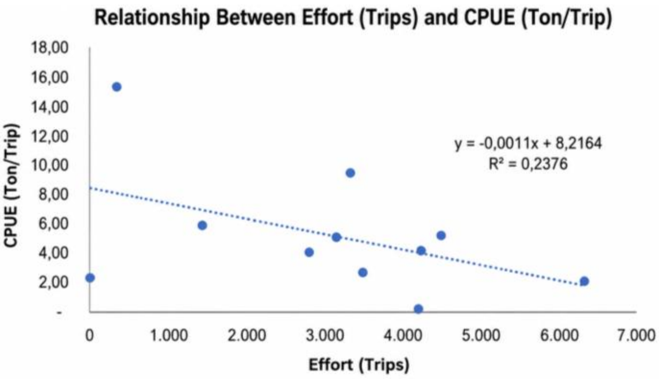

Figure 6. CPUE (Catch Per Unit Effort)

CONCLUSION

Based on the research findings, it can be concluded that *Sardinella lemuru* production in the Bali Strait during the 2014–2024 period exhibits a highly dynamic, cyclical pattern of fluctuations. These fluctuations are influenced by three main factors: fishing intensity, as indicated by the CPUE trend; *Sardinella lemuru* biological cycle, which requires 2–3 years for recovery; and seasonal migration patterns influenced by the oceanographic conditions of the Bali Strait. The collapse phenomenon that occurred during the 2017–2018 period was a result of overfishing practices in the preceding period. The recovery in production observed during the 2020–2024 period underscores the natural resilience of *Sardinella lemuru* population; however, careful management remains essential to prevent the recurrence of collapse cycles.

ACKNOWLEDGMENTS

The author would like to express gratitude to PPN Pengambengan and PPP Muncar for providing catch statistics that were crucial to this study. Appreciation is also extended to the Marine Fisheries Research Center, as well as the fishermen and skippers of the sample vessels, for their assistance and field information provided during the data collection process . The author thanks the academic advisory team and fellow researchers for their valuable scientific input in refining this manuscript. All such support and contributions were instrumental in completing this research.

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