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Research Article

Scaling Digital Fisheries Management: The Role of e-PIT in Enhancing Data Accuracy and Operational Efficiency

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Abstract

The e-PIT system has transformed fisheries management in Indonesia by improving data accuracy, efficiency, and transparency. This study examines the effects of e-PIT from 2022 to 2024, focusing on metrics such as vessel arrivals, catch data, and PHP revenue. A descriptive-exploratory approach was used to compare data before and after e-PIT's implementation. Findings show significant progress: vessel arrivals rose by 475%, catch amounts doubled to 1.167 billion kilograms, and PHP revenue increased by 161% to Rp 951.64 billion in 2024. Daily operations stabilized, with 257 transactions worth IDR 2.6 billion. While a security test found some vulnerabilities like unsecured cookies and outdated server settings, improvements have been made to enhance security, aligning with standards like ISO/IEC 27001. These measures ensure e-PIT's security, scalability, and reliability as a model for digital fisheries governance. The study concludes that e-PIT boosts efficiency, accuracy, and transparency. Recommendations include improving digital infrastructure, cybersecurity, and stakeholder engagement. Despite its focus on specific data and regions, the study offers insights for applying e-PIT in other developing countries, supporting global goals like SDG 14 and the FAO Fisheries Governance Framework.

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1. Introduction

Indonesia, the largest archipelagic country in the world, holds immense potential for fisheries resources, contributing significantly to food security, national revenue, and the livelihoods of millions of coastal communities. (Henriksson *et al*., 2019; Djunarsjah and Handayani, 2021). However, the fisheries sector faces persistent governance challenges, particularly in ensuring accurate data recording, enhancing operational efficiency, and promoting regulatory transparency (Widarmanto, 2018; Liawatimena *et al*., 2020; Natsir *et al*., 2021). Manual systems, which have long been the foundation of fisheries' governance in Indonesia, often result in fragmented data, delays in decision-making, and reduced policy effectiveness (Mangi *et al*., 2013; Utama *et al*., 2017; Nilsson *et al*., 2019). The absence of digital infrastructure further delays the transmission of critical information, impairing swift decision-making processes and weakening the enforcement of fishing regulations. As a result, key mechanisms such as quota enforcement and real-time monitoring, both of which are essential for sustainable fisheries management, are significantly compromised. Without reliable data and timely surveillance, it becomes nearly impossible to track fishing effort, prevent overfishing, or respond proactively to illegal, unreported, and unregulated (IUU) fishing activities. This governance gap ultimately undermines the long-term sustainability of Indonesia's fisheries and hinders the country's ability to align with international best practices in marine resource management (Garcia and Charles, 2008; Purcell and Pomeroy, 2015; Handoyo, 2019; Nilsson *et al*., 2019).

Globally, digital transformation has demonstrated its effectiveness in addressing similar challenges. For example, Vessel Monitoring Systems (VMS) in Europe have improved compliance, management strategies, protected marine ecosystems, and increased data accuracy by up to 85% (Tsakalidis *et al*., 2020; Quaranta *et al*., 2023; Tassetti *et al*., 2022; Chalvantzis *et al*., 2024; Crupi *et al*., 2024). Similarly, electronic reporting systems in Japan have facilitated faster and more accurate catch tracking, enabling authorities to identify fishing trends in real-time and prevent overfishing (Helmond *et al*., 2019). Meanwhile, Norway has successfully implemented a digital licensing system integrated with satellite-based monitoring and automated data collection, which streamlines administrative processes and strengthens quota control (Gullestad *et al*., 2016). In Australia, digitalization in fisheries management plays a vital role, particularly in integrating oceanographic data and catch reports for evidence-based decision-making. Additionally, digital platforms are used to foster transparency and collaborative engagement among stakeholders (Merrifield *et al*., 2019; Teh *et al*., 2020). These systems have enabled the adoption of data-driven decision-making, which is critical for aligning governance practices with sustainability objectives (Smith *et al*., 2020). Despite their success, replicating such technologies in developing countries often faces unique challenges, such as limited technological infrastructure and low digital literacy among stakeholders (Mazuki *et al*., 2020; Grantham *et al*., 2022). Additionally, socioeconomic barriers, including insufficient training and financial incentives, exacerbate these issues, further necessitating the development of localized solutions in fisheries (Nilsson *et al*., 2019; Grantham *et al*., 2022).

To address these challenges, Indonesia's Ministry of Marine Affairs and Fisheries introduced the e-PIT application under the quota and zone based fishing policy. e-PIT represents the first integrated digital platform in Indonesia designed to replace fragmented manual processes with a unified solution (Fitrianah *et al*., 2014; Zulbainarni *et al*., 2020; Arykbaev, 2022; Delimayanti *et al*., 2022; Zainudin *et al*., 2023). The system integrates three critical functions: data recording, operational monitoring, and non-tax state revenue (PNBP) (Kamisetti and Shaligram, 2012; Liawatimena *et al*., 2020; Natsir *et al*., 2021; Yonvitner and Sartin, 2021). By leveraging cutting-edge technology, e-PIT aims to enhance data accuracy, facilitate real-time decision-making, and promote transparency in the fisheries sector. Through features such as real-time reporting, standardized tariffs, and robust security protocols, e-PIT aims to enhance data accuracy, operational efficiency, and governance transparency (Azhar *et al*., 2019; Trionawan *et al*., 2021; Raup *et al*., 2023; Ngabalin, 2024). Furthermore, the platform supports the implementation of standardized fishing quotas and streamlines decision-making processes, reducing redundancies in data collection while aligning governance practices with sustainability objectives.

The implementation of e-PIT in Indonesia has significantly improved fisheries governance, leading to a 205% increase in vessel reporting and a 210% rise in catch documentation. Platforms like the E-Log Book simplify reporting for fishermen, while blockchain ensures traceability, building trust among stakeholders. Moreover, the establishment of databases such as the Regional Fishing Vessel Record (RFVR) aids in combating illegal, unreported, and unregulated (IUU) fishing, contributing to more sustainable fisheries management (Imsamrarn *et al*., 2014; Probst, 2020; Trionawan *et al*., 2021; Gutandjala *et al*., 2023; Alfarisy *et al*., 2024). The adoption of digital technologies extends beyond e-PIT. In Bali's sardine fishery, ICT applications like the Marine ICT-Landing

(MICT-L) system have been implemented to collect digital catch landing data. This participatory approach not only facilitates robust stock assessments but also informs policy decisions regarding total allowable catch (TAC) and spatial productivity. Smart dashboards provide real-time monitoring capabilities for fisheries managers, fostering greater engagement and awareness among stakeholders (Natsir *et al*., 2022).

In recent years, the need for efficient and transparent governance in fisheries management has become increasingly urgent, particularly in resource-constrained settings. While the documented disadvantages are limited, various areas warrant attention. Scalability is crucial as demand increases, necessitating solutions such as cloud-based infrastructure to accommodate diverse technological environments. Enhancing interoperability and integration with existing governmental data systems could facilitate comprehensive data analysis and holistic management. Data processing optimization through advanced analytics or machine learning would enable better real-time processing and decision-making. Improving user experience by creating a more intuitive interface and offering training programs can overcome digital literacy barriers and boost adoption. Incorporating predictive analytics and artificial intelligence can provide stakeholders with real-time insights, enhancing decision-making. Furthermore, strengthening system robustness and data security is vital to maintain trust. The current limited literature on e-PIT highlights the need for further research to gain a deeper understanding of its implementation and impact. Conducting comparative studies with similar systems globally could also yield valuable insights for future development. Thus, focusing on these areas can substantially improve e-PIT's effectiveness and applicability.

This study aims to address these gaps by evaluating the e-PIT platform, a digital solution designed to streamline fisheries governance by integrating data recording, operational monitoring, and PHP revenue management into a single, scalable platform. The fishing fee (PHP) refers to a charge imposed on fishers or fishing companies, calculated as a percentage of the total value of the fish landed. The novelty of e-PIT lies in its holistic approach, offering a comprehensive solution that tackles both operational inefficiencies and the challenges of fragmented governance structures. Here, we show how e-PIT has been successfully implemented in Indonesia to enhance operational efficiency, data accuracy, and governance transparency in the fisheries sector. This research examines not only the impacts of e-PIT on key performance indicators such as vessel arrivals, catch, and PHP revenue collection but also the challenges faced during its adoption, including infrastructure limitations, stakeholder resistance, and the need for user training. By analyzing quantitative data collected between 2022 and 2024, we assess e-PIT's ability to provide a reliable, scalable model for improving fisheries governance. Moreover, this study is grounded in global governance frameworks, particularly the FAO Fisheries Governance Framework and SDG 14 (Life Below Water), which emphasize transparency and inclusive stakeholder participation. By aligning the objectives and outcomes of the e-PIT platform with these internationally recognized benchmarks, this research positions e-PIT not only as a national innovation but also as a scalable and transferable model of digital transformation that supports sustainable fisheries governance.

2. Materials and Methods

2.1 Materials

2.1.1 The equipments

This study employed advanced tools such as the e-PIT platform, encompassing subsystems including SILAT (licensing), SIPALKA (vessel registration), SILOPI (logbook and quota monitoring), PIPP (catch data management), and SIMPONI (financial reporting), to collect comprehensive data on vessel operations, catch, and PHP revenue. Additionally, analytical tools such as Microsoft Excel were utilized for data processing, while Power BI facilitated the creation of detailed visualizations, including trend analyses and heatmaps, to capture the system's operational and financial performance.

2.1.2 The materials

The materials used in this research included key datasets covering vessel arrival records (2022–2024), monthly fish catch reports (2023–2024), and PHP revenue statistics (2023–2024), which served as the foundation for evaluating e-PIT's effectiveness. Supporting materials also included the Standard Operating Procedures (SOPs) for fishing port management, which provided a structured framework for analyzing operational workflows, including vessel arrivals, logbook submissions, and compliance protocols. Furthermore, the study incorporated the findings of a comprehensive Pentest evaluation of the e-PIT system, which identified critical vulnerabilities and outlined the mitigation strategies implemented to enhance system security. Collectively, these tools and materials underpinned the rigorous analysis of e-PIT's contributions to improving fisheries governance, operational efficiency, and data transparency.

2.1.3 Ethical approval

This study does not require approval because it does not use experimental animals. The study adhered to strict ethical guidelines throughout the research process. All data used in the analysis were anonymized and obtained with approval from Indonesia's Ministry of Marine Affairs and Fisheries. No personal or sensitive information was disclosed, and all analyses were conducted in compliance with ethical standards for fisheries governance research. Stakeholder feedback, where applicable, was anonymized to ensure unbiased reporting and confidentiality.

2.2 Methods

2.2.1 Research design

This study employs a descriptive-exploratory research design to evaluate the implementation and impact of the e-PIT application in Indonesia's fisheries sector. The research focuses on improvements in operational efficiency, data accuracy, and governance transparency, which are essential for modernizing fisheries governance. By integrating quantitative analysis of operational data and qualitative process evaluations, the study provides a comprehensive understanding of how e-PIT transforms vessel reporting, quota monitoring, and financial compliance. A longitudinal approach, comparing data from 2022 (pre-e-PIT) to 2023 and 2024 (post-e-PIT), allows for a robust evaluation of the system's impact on fisheries governance.

2.2.2 Data sources and collection

The data for this study were derived from secondary sources managed by Indonesia's Ministry of Marine Affairs and Fisheries. These include operational data from the e-PIT system and standard operating procedures (SOPs) for port management. The datasets encompass vessel arrivals, catch, PHP revenue, daily performance metrics, and security evaluation records. Vessel arrival data were collected monthly and annually for the years 2022 to 2024, enabling the analysis of stakeholder compliance and operational improvements following the adoption of e-PIT. Catch data, recorded monthly for 2023 and 2024, highlights advancements in reporting accuracy, while PHP revenue data, including annual and daily metrics, illustrates financial efficiency and improved governance practices. Daily performance metrics, such as billing rates and standardized PHP tariffs per kilogram, reflect operational consistency achieved through e-PIT. Additionally, data from a comprehensive Pentest evaluation identifies system vulnerabilities and documents corrective actions implemented during the study period.

The data collection process was guided by the Standard Operating Procedures (SOPs) for fishing port management. These SOPs outline the workflows for vessel arrival and logbook submission, self-assessment, fishing levy payment, and the submission of port clearance for the next trip departure. These SOPs define the responsibilities of key stakeholders, including harbor masters, fisheries inspectors, enumerators, business owners, and captains, and provide the foundation for analyzing operational processes. Figure 1 illustrates the implementation of SOPs in fishing port management, showcasing the sequence of activities and role-based responsibilities for arrival and departure workflows.

This integration of SOPs and e-PIT data collection systems ensures that the study captures both operational workflows and the digital transition to e-PIT. The timeline spans three years, covering manual processes in 2022 and the digital transformation in 2023 and 2024, to provide a comprehensive evaluation of e-PIT's impact.

2.2.3 Variables of interest

This study evaluates three primary variables to assess the impact of e-PIT on fisheries governance. The first variable, operational efficiency, is examined through SOP workflows for vessel arrivals and departures, compliance with logbook submissions, and streamlined processes enabled by e-PIT. This variable highlights how e-PIT simplifies task delegation among stakeholders and improves efficiency in reporting and clearance activities. The second variable, data accuracy, is assessed through changes in catch reporting and vessel documentation, focusing on reducing delays and discrepancies. Improvements in data accuracy demonstrate e-PIT's ability to enhance reporting reliability, which is critical for decision-making. The third variable, governance transparency, is evaluated through PHP revenue data, including total collections and average daily metrics, which highlight financial accountability. Additionally, the outcomes of the Pentest evaluation provide insights into the security framework of e-PIT, further contributing to its reliability and transparency.

2.2.4 Security and system assessment

The e-PIT application integrates seven core systems that are interconnected, including the vessel licensing system (SILAT), vessel registration (SIPALKA), quota monitoring (SILOPI), and catch reporting (PIPP). This integration streamlines fisheries governance into a single digital platform, significantly improving data accuracy and operational efficiency. However, since the system operates online,

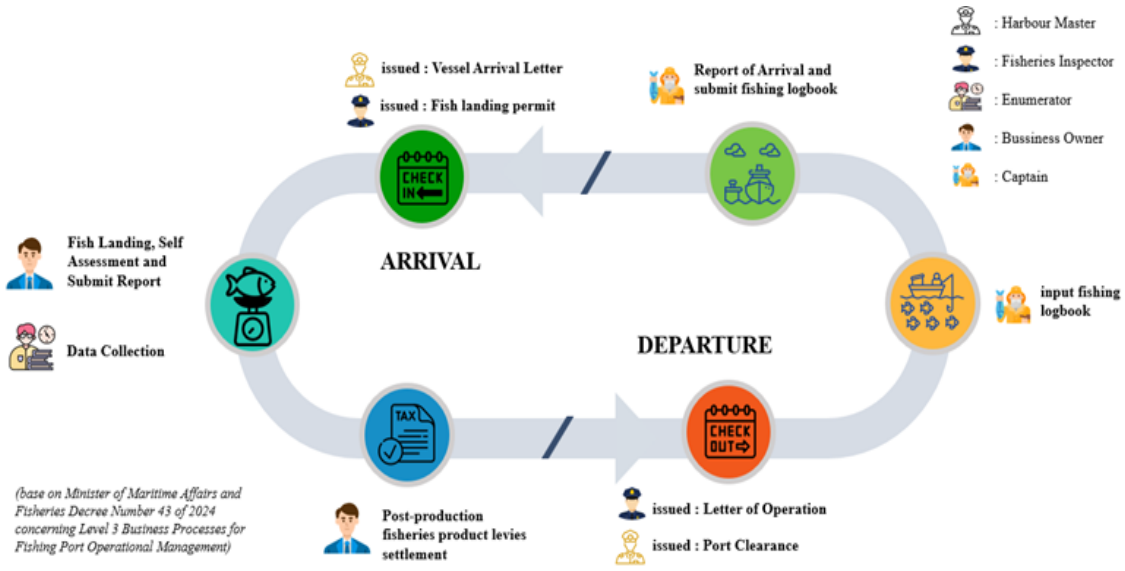

Figure 1. Implementation of standard operating procedures for fishing port management.

it is essential to ensure that all data and services are protected from potential cybersecurity threats.

To address this, a comprehensive security assessment known as penetration testing (Pentest) evaluation was conducted. This evaluation involves simulating cyberattacks by security experts to identify vulnerabilities in the system, network, and application before these weaknesses can be exploited by malicious actors, The primary objective of this assessment is to ensure that the system remains protected from both external threats and internal errors, while also safeguarding data during transmission between users and the server. For example, the X-Frame-Options header is used to prevent clickjacking attacks, a manipulation technique where users are unknowingly tricked into clicking concealed elements. The assessment also included reviews of other HTTP security headers, insecure cookies, and outdated server configurations, all of which could expose the system to risk, such as session hijacking, where attackers can take over legitimate user sessions. This security evaluation is not merely an effort to find vulnerabilities; it is a systematic strategy to understand potential risks, assess their impact, and implement appropriate mitigation measures. The implementation of these findings has significantly improved the reliability of the e-PIT's system, while also ensuring its scalability as a secure and trusted model of digital governance. Figure 2 provides a detailed overview of e-PIT's architecture, illustrating how the integration of integrated services works together to streamline licensing, quota compliance, and PHP revenue reporting to a digital interface.

This system assessment underscores the importance of secure integration among the seven key services as shown in Figure 2, enabling seamless workflows while safeguarding data integrity and reliability.

2.2.5 Limitations

While this study provides a comprehensive evaluation of e-PIT, it is subject to certain limitations. First, reliance on secondary data restricts the incorporation of qualitative insights from stakeholders directly involved in the system's implementation. Second, the security evaluation focuses on technical vulnerabilities within the e-PIT system, without addressing broader organizational risks. Third, the three-year timeframe captures short- to medium-term impacts but may not fully reflect the long-term implications of e-PIT. Despite these constraints, the methodology offers a robust framework for evaluating e-PIT's contributions to fisheries governance and its scalability as a digital governance model for other developing nations.

2.3 Analysis Data

The study employs a combination of quantitative and process-oriented methods to evaluate e-PIT's effectiveness. Trend analysis is conducted to identify patterns and changes in vessel arrivals, catch reporting, and PHP revenue before and after e-PIT implementation. This approach highlights percentage growth and cumulative improvements, particularly in compliance and efficiency metrics. Descriptive statistics, including averages and growth rates, are used to interpret operational and governance metrics, providing a detailed understanding of the system's

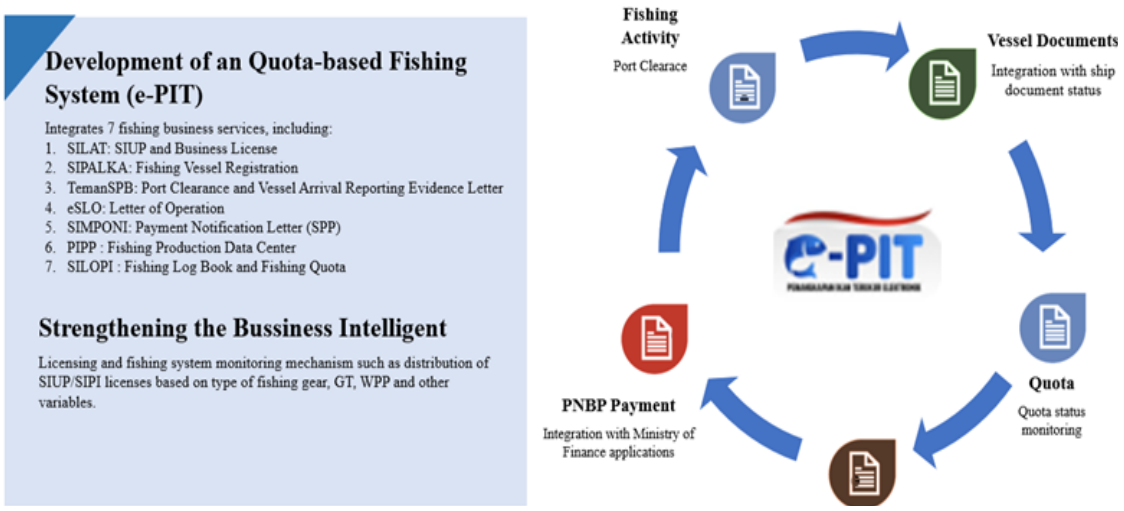

Figure 2. Architecture and aof the e-PIT application.

performance. Process evaluations of SOP workflows were conducted to analyze the alignment of roles and responsibilities among stakeholders, focusing on efficiency improvements. Additionally, heatmaps are generated to visualize seasonal variations and system performance during peak operational periods.

To quantitatively assess the impact of e-PIT on ship arrival rates, a paired t-test was conducted comparing monthly ship arrivals before and after e-PIT implementation. The primary assumption for this test was the normality of the differences between the paired observations (pre- and post-e-PIT), validated through descriptive statistics and graphical methods such as Q-Q plots. A two-tailed test was applied with a significance level (α) set at 0.05. The null hypothesis, asserting no difference in mean ship arrivals before and after e-PIT implementation, was rejected if the p-value was ≤ 0.05. To further evaluate the impact of the e-PIT system on various fisheries management outcomes, three linear regression models were constructed using a dummy variable for e-PIT implementation (0 = pre-implementation, 1 = post-implementation). These models aimed to assess the effects of e-PIT on production, PHP Revenue and the number of ship permits. The general structure of the models was defined as:

$$Y=\beta0+\beta1(e\text{-}PIT)+\epsilon \quad \text{.....(i)}$$

Where:

$\beta0$ represents the intercept (baseline pre-e-PIT),

$\beta1$ is the coefficient measuring the effect of e-PIT,

ϵ denotes the error term.

Hypotheses were formulated as follows:

H_1: e-PIT implementation significantly increases monthly ship arrivals.

H_2: e-PIT implementation significantly enhances production outputs.

H_3: e-PIT implementation significantly improves PHP Revenue.

H_4: e-PIT implementation significantly raises the number of ship permits issued.

3. Results and Discussion

3.1 Results

This study evaluates the implementation of the e-PIT system as a digital fisheries management tool aimed at improving data accuracy, operational efficiency, and governance transparency. The analysis focuses on key variables, including vessel reporting, catch monthly and annually from 2022 to 2024, catch documented monthly for 2023 and 2024, and PHP revenue collection-analyzed as both total annual and average daily revenue for the same period. Additionally, daily indicators such as average daily billings and revenue per kilogram are examined to assess system performance and efficiency. By integrating these metrics, the study investigates the impact of e-PIT in advancing digital governance in Indonesia's fisheries sector. The research further explores the scalability of e-PIT as a model for digital transformation in fisheries management, particularly for other developing countries facing similar socio-economic challenges. This aligns with the study's broader objective of quantifying how digital tools like e-PIT can enhance sustainable governance through data-driven decision-making.

3.1.1 Trends in vessel arrivals before and after e-PIT implementation

The paired t-test revealed a statistically significant surge in ship arrivals post-e-PIT ($t = -3.48$, $p = 0.005$). Monthly averages increased from 1,558.8 (pre-e-PIT) to 31,097.5 (post-e-PIT), indicating a dramatic improvement in operational efficiency and data reporting compliance. This supports H_1 with strong evidence ($\alpha < 0.01$).

The monthly vessel arrivals data from 2022 to 2024 in Figure 3 reveals a significant upward trend following the implementation of e-PIT. In 2022, prior to e-PIT adoption, total vessel arrivals were recorded at 18,706, with an average of 1,559 vessels per month. After the implementation of e-PIT in 2023, the total arrivals increased to 42,960, averaging 3,580 vessels per month, reflecting a 230% increase compared to 2022. This upward trend continued in 2024, where total arrivals reached 88,788, averaging 7,399 vessels per month, which is a remarkable 475% increase compared to 2022.

To illustrate this trend, both line and clustered bar charts are presented in Figure 4, depicting a consistent and substantial monthly increase. The highest growth is observed in the second half of each year, aligning with seasonal fishing activities and the enhanced operational capacity facilitated by e-PIT. This significant increase highlights the system's effectiveness in improving data accuracy and attracting more industry stakeholders to comply with the system. Furthermore, the increase in vessel reporting signifies improved operational efficiency, demonstrating the scalability and reliability of e-PIT as a digital solution for fisheries management.

The heatmap provides a clear visualization of monthly vessel arrivals from 2022 to 2024, demonstrating the significant impact of e-PIT implementation on fisheries governance. With 2024 placed at the top to highlight the most recent data, followed by 2023 and 2022, the color gradient (green to red) reflects a dramatic increase in vessel activity post-e-PIT. In 2022, prior to e-PIT, vessel arrivals were

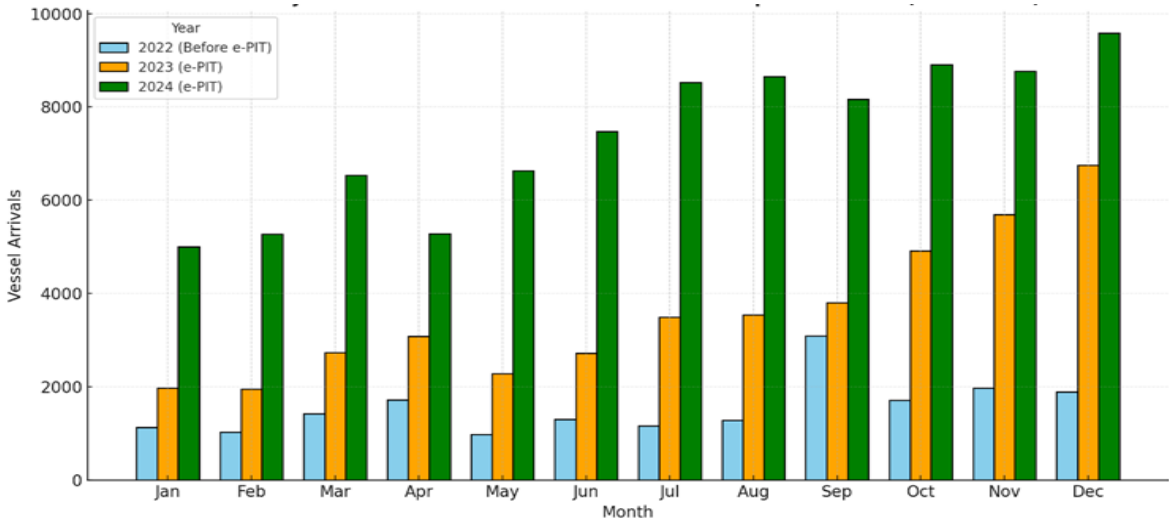

Figure 3. Impact of e-PIT implementation on monthly vessel arrivals: A comparison of 2022-2024.

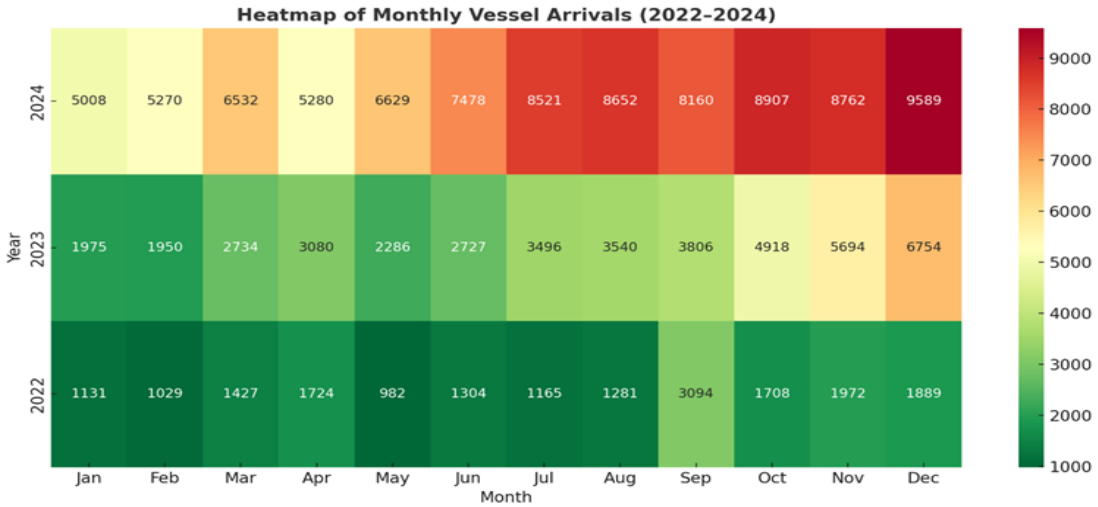

Figure 4. Monthly vessel arrivals heatmap: impact of e-PIT implementation (2022–2024).

relatively low and consistent, as indicated by green tones across most months. However, following e-PIT's adoption in 2023, vessel arrivals increased by 230% year-on-year, with key months transitioning to orange and red tones. By 2024, arrivals reached their peak, with a 475% increase compared to 2022, as red tones dominated throughout the year, particularly during the peak fishing months of October to December. This growth underscores e-PIT's effectiveness in enhancing operational efficiency, as the system successfully facilitated higher compliance and reporting accuracy among stakeholders. The visualization also aligns with seasonal trends, indicating that e-PIT's integration supports data-driven planning and decision-making aligned with natural cycles in fisheries. These findings directly support the hypothesis that e-PIT improves data accuracy and operational efficiency while addressing the research objective of evaluating its role in scaling sustainable fisheries governance. Moreover, the results affirm e-PIT's scalability as a digital management model, offering valuable insights for adoption in similar socio-economic contexts globally.

3.1.2 Impact of e-PIT on catch

For production outputs, the dummy regression model showed a positive coefficient for e-PIT (β = 484,527.5, p = 0.081), suggesting an increase in production by approximately 484,528 units post-implementation. While the effect was directionally supportive of H_2, statistical significance was marginal at α = 8.1%, slightly above the conventional 5% threshold. The model explained 69.1% of the variance ($R^2 = 0.691$), indicating a robust relationship.

The line chart illustrates the monthly catch trends for 2023 and 2024, highlighting the substantial impact of e-PIT on improving operational efficiency and data accuracy. In 2023, total catch reached 555.2 million kilograms, with an average of 50.47 million kilograms per month, while in 2024, catch rose to 1.167 billion kilograms, averaging 97.31 million kilograms per month-a remarkable 210% increase year-on-year (Figure 5).

The chart reveals a consistent upward trend in 2024 compared to 2023, with notable peaks observed in July and October - December, aligning with heightened fishing activities during these months. The smoother and more robust catch pattern in 2024 underscores the system's effectiveness in enhancing data reporting and operational transparency, as e-PIT facilitates accurate and timely data submission from stakeholders.

This growth validates the hypothesis that e-PIT significantly improves operational efficiency and data accuracy in fisheries management. The system not only addresses previous under-reporting challenges but also ensures reliable documentation of catch trends, enabling more effective policy formulation and decision-making. Furthermore, the scalability of e-PIT is demonstrated by its capacity to manage larger data volumes while maintaining consistency, positioning it as a replicable model for fisheries governance in other developing nations.

3.1.3. PHP trends before and after e-PIT implementation

The stacked bar chart illustrates the cumulative monthly PHP revenue for 2023 and 2024, highlighting the significant impact of e-PIT on operational efficiency and revenue collection accuracy. In 2023, total PHP revenue amounted to Rp 590.85 billion, increasing significantly to Rp 951.64 billion in 2024, reflecting a 161% year-on-year growth. The cumulative contributions of each month show that the fourth quarter (October–December) consistently accounted for the highest PHP revenue in both years, aligning with increased fishing activities during this period (Figure 6).

Key months such as October and November 2024 demonstrate the most significant growth compared to their 2023 counterparts, driven by improved compliance and accuracy in reporting through e-PIT. The system also facilitated more consistent PHP revenue collection throughout the year in 2024, reducing reliance on peak months and reflecting enhanced operational capacity. This consistent growth pattern indicates that e-PIT successfully addressed challenges in the traditional PHP collection system, such as under-reporting and delays in submission, by ensuring timely and accurate reporting.

These findings validate the hypothesis that e-PIT significantly improves operational efficiency and PHP revenue accuracy. Furthermore, the scalability of e-PIT is evident in its ability to manage increased data volumes without compromising accuracy or efficiency. This positions e-PIT as a replicable digital governance model for fisheries management in other developing nations facing similar socio-economic challenges. The success of e-PIT demonstrates the potential for leveraging digital technologies to achieve sustainable governance, aligning with global efforts to modernize fisheries management systems.

Refer to our statistical analysis, the PHP exhibited a non-significant increase (β = 301.25, p = 0.281), with e-PIT accounting for only 14.3% of variance ($R^2 = 0.143$). This fails to support H_3, implying that while PHP revenue improved nominally, other

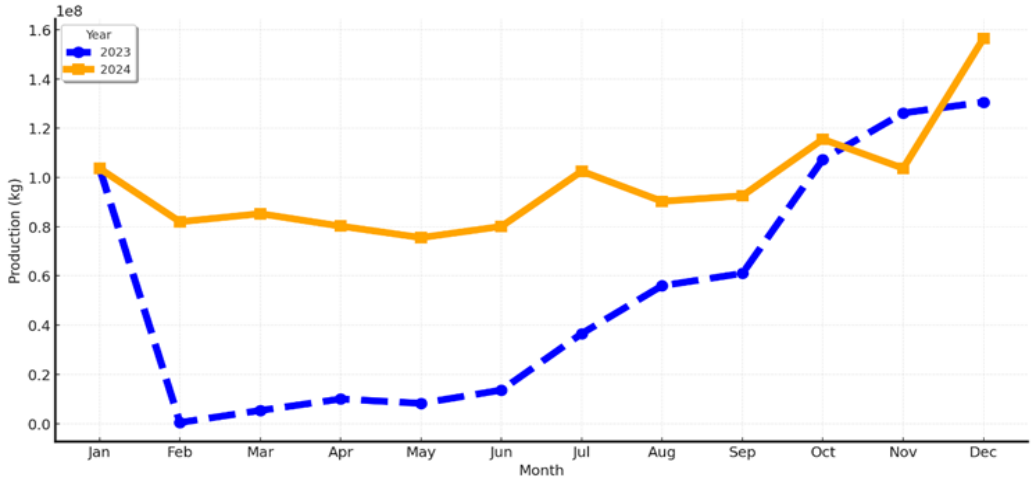

Figure 5. Impact of e-PIT on operational efficiency and data accuracy in monthly trends (2023–2024).

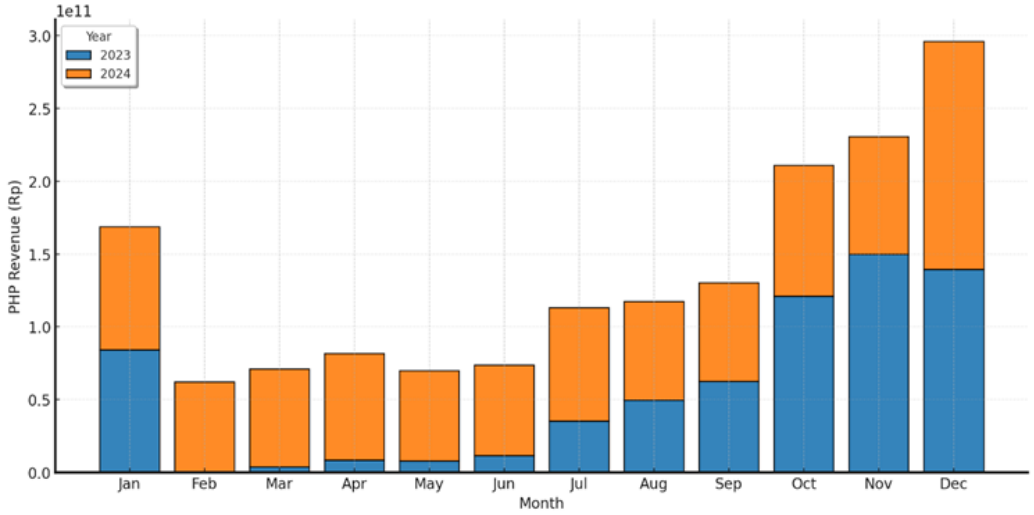

Figure 6. Cumulative monthly PHP revenue trends before and after e-PIT implementation (2023–2024).

unmeasured factors likely influenced PHP outcomes.

3.1.4 Daily performance metrics of e-PIT

The combination chart, as shown in Figure 7, provides a comprehensive view of monthly catch alongside key daily performance metrics (billing and PHP per kilogram) for 2024. The monthly catch (blue bars) shows consistent increases, peaking in October and December, which aligns with high fishing activity periods. This pattern reflects the system's ability to handle significant data volumes during peak months while maintaining operational efficiency.

The daily billing rate (blue line), maintained at a stable 257 billing/day, demonstrates the system's consistency in processing transactions, irrespective of fluctuations in catch. Similarly, the PHP per kilogram (orange dashed line) remains constant at Rp 815/kg, indicating a standardized tariff mechanism enabled by e-PIT, which contributes to PHP revenue transparency and reliability.

To quantitatively assess the impact of e-PIT on permit issuance, a regression analysis was conducted, revealing a highly significant coefficient for e-PIT ($\beta = 7{,}404.8, p = 0.007$). This indicates a substantial increase in the number of permits post-implementation, rising from a baseline of 5,916.7 to 13,321.5. The model's explanatory power is exceptionally high, with an R^2 value of 0.936, meaning that 93.6% of the variance in permit numbers is accounted for by the e-PIT implementation. This strong statistical significance validates Hypothesis H_4, which posits that e-PIT streamlines administrative processes, leading to increased permit issuance.

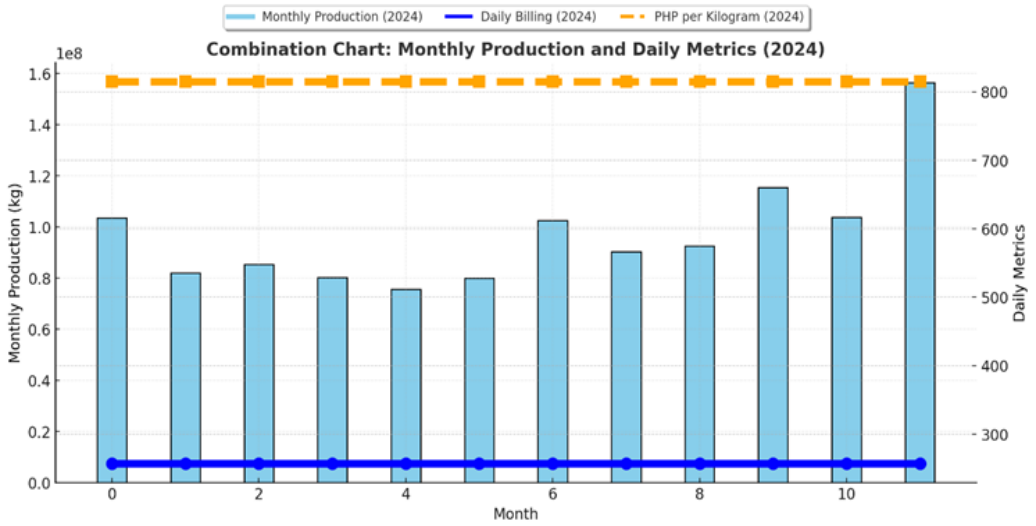

Figure 7. Monthly catch and daily performance metrics of e-PIT in 2024.

3.1.5 Pentest analysis: scaling digital fisheries management

The security assessment (Pentest) of the e-PIT portal plays a pivotal role in evaluating its reliability as a scalable digital fisheries management system (Figure 8). The e-PIT application is designed to enhance data accuracy, operational efficiency, and governance in Indonesia's fisheries sector. However, the Pentest revealed critical vulnerabilities that could compromise the system's performance and scalability if left unaddressed.

Key findings include the absence of essential HTTP security headers, such as X-Frame-Options, HSTS, and X-Content-Type-Options, making the portal vulnerable to Clickjacking, downgrade attacks, and MIME sniffing. Additionally, cookies without Secure and HttpOnly flags increased the risk of session hijacking. The use of outdated encoding methods and an obsolete Apache version introduced further risks, while unrestricted HTTP methods and visible administrative directories highlighted gaps in access control.

```
- Nikto v2.5.0
---------------------------------------------------------------------------
+ Target IP:          [redacted]
+ Target Hostname:    [redacted]
+ Target Port:        443
---------------------------------------------------------------------------
+ SSL Info:        Subject:  /CN=[redacted]
                   Ciphers:  ECDHE-RSA-AES128-GCM-SHA256
                   Issuer:   /C=GB/ST=Greater Manchester/L=Salford/O=Sectigo Limited/CN=Sectigo RSA Domain Validation Secure Serv
er CA
+ Start Time:         2025-01-06 02:20:01 (GMT-5)
---------------------------------------------------------------------------
+ Server: Apache/2.4.25
+ /pit/: The anti-clickjacking X-Frame-Options header is not present. See: https://developer.mozilla.org/en-US/docs/Web/HTTP/Head
ers/X-Frame-Options
+ /pit/: The site uses TLS and the Strict-Transport-Security HTTP header is not defined. See: https://developer.mozilla.org/en-US
/docs/Web/HTTP/Headers/Strict-Transport-Security
+ /pit/: The X-Content-Type-Options header is not set. This could allow the user agent to render the content of the site in a dif
ferent fashion to the MIME type. See: https://www.netsparker.com/web-vulnerability-scanner/vulnerabilities/missing-content-type-h
eader/
+ /pit/: Cookie ci_session_epit created without the secure flag. See: https://developer.mozilla.org/en-US/docs/Web/HTTP/Cookies
+ /pit/: Cookie ci_session_epit created without the httponly flag. See: https://developer.mozilla.org/en-US/docs/Web/HTTP/Cookies
+ No CGI Directories found (use '-C all' to force check all possible dirs)
+ /pit/: The Content-Encoding header is set to "deflate" which may mean that the server is vulnerable to the BREACH attack. See:
http://breachattack.com/
+ Apache/2.4.25 appears to be outdated (current is at least Apache/2.4.54). Apache 2.2.34 is the EOL for the 2.x branch.
+ OPTIONS: Allowed HTTP Methods: POST, OPTIONS, HEAD, GET .
+ /: Web Server returns a valid response with junk HTTP methods which may cause false positives.
+ /pit/web/: Cookie bahasa created without the secure flag. See: https://developer.mozilla.org/en-US/docs/Web/HTTP/Cookies
+ /pit/web/: Cookie bahasa created without the httponly flag. See: https://developer.mozilla.org/en-US/docs/Web/HTTP/Cookies
+ /pit/admin/: This might be interesting.
^[[A^[[A^[[A^[[A^[[A^[[A^[[B^[[B^[[B^[[B^[[B^[[B^[[B^[[B^[[B^[[B^[[B^[[B^[[A^[[A^[[A^[[A^[[A^[[A^[[A^[[A^[[A^[[A^[[A^[[A^[[A^
+ ERROR: Error limit (20) reached for host, giving up. Last error: opening stream: can't connect: Connect failed: ; Connection ti
med out at /var/lib/nikto/plugins/LW2.pm line 5254.
: Connection timed out
+ Scan terminated: 20 error(s) and 12 item(s) reported on remote host
+ End Time:           2025-01-06 02:30:07 (GMT-5) (606 seconds)
---------------------------------------------------------------------------
+ 1 host(s) tested
```

Figure 8. A Comprehensive security and performance evaluation of e-PIT: Strengthening Indonesia's digital fisheries management.

Addressing these vulnerabilities is crucial to ensure that e-PIT serves as a reliable and secure model for data-driven fisheries management. Mitigation measures were implemented, including updating HTTP security headers, securing cookies, removing insecure encoding methods, and updating the Apache server. Access to administrative directories was restricted, and HTTP methods were limited to essential functions, strengthening the system's overall security framework.

These improvements align with the study's broader objective of demonstrating e-PIT's scalability for other developing nations. By enhancing its security, e-PIT ensures the integrity of fisheries data and operational transparency, critical for achieving sustainable fisheries governance. This analysis emphasizes that robust security is foundational to scaling digital solutions like e-PIT across varying socio-economic contexts.

The implementation of e-PIT has led to significant improvements in vessel arrivals, catch, and PHP revenue collection, as evidenced by integrated data and trends. Vessel arrivals increased by 475%, from 18,706 arrivals in 2022 to 88,788 arrivals in 2024, demonstrating enhanced compliance and operational efficiency. Catch doubled from 555.2 million kg in 2023 to 1.167 billion kg in 2024, reflecting improved data accuracy and transparency. PHP revenue experienced a 161% growth, increasing from Rp 590.85 billion (2023) to Rp 951.64 billion (2024), highlighting the system's capability to streamline PHP revenue collection processes. Furthermore, daily metrics such as 257 billing/day and a stable tariff rate of Rp 815/kg underscore the system's consistency and scalability in managing fisheries governance.

The implementation of e-PIT has led to significant improvements in operational efficiency, data accuracy, and governance transparency, as demonstrated by increased vessel arrivals, catch, and PHP revenue. However, a comprehensive security assessment (Pentest) revealed critical vulnerabilities in the system, including missing HTTP headers, outdated encoding methods, and unrestricted access controls. Mitigation measures addressed these risks, ensuring the reliability and scalability of e-PIT. By enhancing both operational and security frameworks, e-PIT provides a robust model for sustainable fisheries governance that is adaptable to other socio-economic contexts.

3.2 Discussion

3.2.1 Enhancing fisheries governance through e-PIT: addressing challenges and driving operational efficiency

The implementation of e-PIT in Indonesia has revolutionized fisheries governance by effectively addressing key challenges such as data inaccuracy, inefficiency, and lack of transparency. Unlike previous systems, e-PIT integrates vessel reporting, catch, and PHP revenue data into a centralized platform, leading to a remarkable 475% increase in vessel arrivals from 2022 to 2024. The use of cutting-edge technologies, such as IoT for real-time data collection and blockchain for ensuring data security and transparency, has addressed issues of inaccurate reporting and built trust among stakeholders (Probst, 2020; Alfarisy *et al*., 2024; Alsharabi *et al.,* 2024). This transformation not only enhances compliance but also improves operational efficiency and the management of fisheries resources, aligning with global frameworks like the FAO Fisheries Governance Framework. By consolidating operational and financial data, e-PIT enables faster and more accurate decision-making, while also streamlining the monitoring and management of catch.

This digital transformation, however, does not occur in isolation. It is deeply embedded within the broader evolution of Indonesian fisheries governance, which has undergone significant transitions from the pre-independence era to the present. A key milestone in this ongoing transformation is the recent adoption of the quota and zone-based fishing policy, a major paradigm shift from the traditional input control approach—which focused on limiting fishing efforts (e.g., through licensing and gear restrictions)—to an output control approach, which regulates the actual amount of fish that can be harvested (Suherman *et al,* 2025). This policy aims to curb overexploitation by setting scientifically-informed catch quotas and defining fishing zones, thereby ensuring that extraction aligns with the regenerative capacity of fish stocks

While e-PIT has shown positive results, there are challenges that need to be addressed, such as initial resistance to adoption and the need for stronger infrastructure in remote areas. Therefore, optimizing infrastructure and providing more comprehensive training for users is critical to ensuring the system is implemented uniformly across Indonesia (Trionawan *et al*., 2021; Deng, 2024). The success of e-PIT in Indonesia offers a replicable model for other developing nations facing similar challenges with data fragmentation and uncertainty in fisheries governance. The integrated model of e-PIT provides a scalable solution that strengthens sustainable fisheries governance and supports global goals like SDG 14 (Life Below Water) (Kim *et al*., 2024).

However, further research is needed to evaluate the long-term impact of e-PIT, particularly regarding the sustainability of fisheries resources and the system's application in regions with infrastructure challenges.

3.2.2 Impact of e-PIT on catch: enhancing operational efficiency and data accuracy

The implementation of e-PIT in Indonesia has significantly improved catch reporting by addressing long-standing issues such as under-reporting, inefficiencies, and lack of data accuracy. Total catch surged by 210% from 555.2 million kilograms in 2023 to 1.167 billion kilograms in 2024, with monthly averages rising from 50.47 million kilograms to 97.31 million kilograms. This improvement reflects e-PIT's ability to support accurate and timely data submissions, particularly during seasonal peaks from October to December 2024. The system's integration of IoT for real-time data collection and blockchain for data security ensures greater transparency and operational efficiency. Compared to previous systems, such as those in South Asia and Southeast Asia, e-PIT's centralized platform and robust infrastructure address challenges in scalability and integration, setting a new benchmark for comprehensive fisheries governance (Pierre *et al.,* 2024; Sun *et al.,* 2024).

Despite its successes, e-PIT faces challenges including stakeholder resistance and infrastructure limitations in remote areas. To overcome these, optimizing infrastructure and expanding digital literacy are critical for sustained growth and long-term success. e-PIT's strengths lie in its centralized integration of operational and financial data, which improves transparency and governance standards. However, the system's scalability and ability to handle seasonal fluctuations without compromising data accuracy remain crucial to its ongoing effectiveness (Alonge *et al*., 2024). To overcome infrastructure limitations, the Indonesian government has prioritized the expansion of digital connectivity through its national digital transformation agenda. The Ministry of Communication and Informatics (Kominfo) has implemented a comprehensive roadmap (2021–2024) that includes deploying SATRIA-1, a high-throughput multifunction satellite with a capacity of 150 Gbps, aimed at providing internet access to 150,000 public facilities in underserved regions. Additionally, the government has expanded terrestrial and subsea fiber optic networks, covering over 348,000 kilometers across Indonesia, and installed more than 559,000 base transceiver stations to strengthen connectivity in remote areas (Azzahra and Amanta, 2021). Enhanced infrastructure will enable wider adoption of e-PIT in remote fishing communities, increasing vessel reporting compliance and catch documentation accuracy. Projections suggest that improved connectivity could lead to an additional 30–50% increase in vessel reporting and data submissions within two years. This would build on the current 205% rise in vessel reporting achieved since e-PIT's implementation.

3.2.3 PHP trends before and after e-pit implementation: enhancing PHP revenue collection and transparency

The implementation of e-PIT has significantly enhanced revenue collection in Indonesia, evidenced by a 161% increase in total PHP revenue, from Rp 590.85 billion in 2023 to Rp 951.64 billion in 2024. This growth can be attributed to the standardization of PHP revenue collection processes, including real-time billing and the introduction of a fixed tariff rate of Rp 815/kg, which has mitigated issues of under-reporting and ensured timely, accurate financial reporting. Monthly PHP revenue trends, as illustrated in the stacked bar chart, indicate consistent contributions across the year, reducing reliance on peak months and stabilizing overall PHP revenue flow. This contrasts with the previous systems in South Asia and Latin America, which faced challenges with transparency and PHP revenue consistency. Unlike those systems, e-PIT integrates both financial and operational metrics into a centralized platform, providing policymakers with a comprehensive, transparent view of revenue flows (Rahman *et al.*, 2019; Garcia *et al.*, 2021).

In Indonesia, prior to recent reforms, fisheries management primarily focused on a licensing system that did not impose clear limits on the number of fish that could be caught by each vessel. This lack of catch quotas made it difficult to regulate fishing activities effectively and ensure that catches remained within sustainable ecological boundaries (Probst, 2020). Moreover, the generation of PHP revenue (PNBP) from the fisheries sector was largely based on pre-production permits rather than the actual volume of fish landed, potentially leading to a disconnect between fishing activity and revenue collected. Issues such as illegal payments at ports and the lack of control fishermen had over fish prices due to the influence of middlemen further complicated the sector's financial landscape (Alfarisy *et al*., 2024). The sheer size of Indonesia's marine territory also contributed to difficulties in enforcing regulations and monitoring fishing activities effectively, leading to indications that a majority of the country's fisheries were fully exploited, with illegal fishing regulations not fully enforced. Under-reporting of catches was also identified as a significant impediment to accurate data collection and effective management. The introduction of e-PIT also signifies a move towards the standardization of revenue collection

processes within the fisheries sector (Alsharabi *et al.*, 2024). The application is intended for the calculation of post-production PNBP through a system of self-assessment by fishing vessels. The planned implementation of e-PIT for calculating PNBP post-production is expected to occur once the regulations concerning the procedure for determining the value of fish production at the time of landing, based on the fishing vessel captain's calculation, come into effect. This shift from potentially inconsistent or less transparent methods to a standardized, post-production assessment facilitated by e-PIT is likely to contribute to more accurate revenue calculations.

FAO Fisheries Governance Framework (2021) highlights the potential of e-PIT alignment to contribute to global efforts aimed at sustainable fisheries management. Enhanced transparency, made possible by e-PIT, encourages public oversight and fosters trust in government operations, as the public can now directly track revenue flows and compliance (Tanjung *et al*., 2024). However, challenges remain, such as stakeholder resistance during the initial stages of adoption and the need for continuous training to ensure sustained improvements in revenue collection. Addressing these issues is critical for the long-term success and scalability of e-PIT as a digital fisheries governance model (Ikwuanusi *et al*., 2024).

3.2.4 Pentest analysis: scaling digital fisheries management

The Pentest analysis of the e-PIT system has revealed several critical vulnerabilities that could compromise its security and operational integrity. Key vulnerabilities include the absence of essential HTTP security headers (such as X-Frame-Options, HSTS, and X-Content-Type-Options), insecure cookies, and outdated server configurations. These issues expose the system to risks such as Clickjacking, session hijacking, and unauthorized access (Sebrina *et al*., 2024; Lachkov *et al*., 2022). To mitigate these risks, proactive measures were taken, including updating server protocols, implementing secure cookies, removing insecure encoding methods, and restricting access to administrative directories. These steps have strengthened e-PIT's security framework, improving both its operational reliability and data integrity.

As a significant government digital platform, the e-PIT system is inherently susceptible to a range of common cyber threats that could potentially compromise the confidentiality, integrity, and availability of the system and the sensitive data it manages. These threats include malware infections, such as viruses, worms, and spyware, which could infiltrate the system through various means, including infected files or compromised websites. Phishing attacks, designed to trick users into revealing their login credentials or other sensitive information, pose a significant risk, particularly targeting user accounts with elevated privileges. Ransomware, as evidenced by the attack on the National Data Centre, could encrypt critical data within the e-PIT system, rendering it inaccessible until a ransom is paid, potentially disrupting vital fisheries management operations. Denial-of-service (DoS) and distributed denial-of-service (DDoS) attacks could overwhelm the system's resources, making it unavailable to legitimate users, which could hinder the timely reporting of fishing activities and revenue collection. The increasing sophistication of these threats, potentially involving the use of artificial intelligence, means that malicious actors may employ more targeted and evasive techniques to exploit vulnerabilities within the e-PIT system.

By addressing these vulnerabilities, e-PIT aligns with global cybersecurity standards, such as ISO/IEC 27001, ensuring the system's scalability as a secure digital governance model. Unlike earlier systems in South Asia and Latin America, which struggled with operational disruptions due to inadequate security measures (Smith *et al.*, 2020; Garcia *et al.*, 2021), e-PIT demonstrates the importance of robust cybersecurity in enhancing operational resilience and stakeholder trust. By prioritizing security, e-PIT ensures the integrity of fisheries data and operational transparency, crucial for achieving sustainable fisheries governance. This proactive approach to cybersecurity positions e-PIT as a replicable framework for digital transformation in other developing nations, highlighting its potential for global scalability and security in fisheries management.

3.2.5 Scalability of e-PIT as a model for digital transformation for developing countries

The success of e-PIT in Indonesia demonstrates its potential as a scalable model for fisheries governance in other developing countries. The system's ability to increase vessel reporting by 205% and catch documentation by 210% highlights its capacity to address critical challenges such as underreporting, IUU fishing, and inefficient resource management. These achievements are particularly relevant for nations with limited fisheries monitoring infrastructure, where digital transformation can bridge gaps in data collection, compliance, and policy enforcement.

A key factor contributing to e-PIT's scalability is its integration of advanced technologies such as IoT

and blockchain. IoT devices, including GPS trackers, enable real-time monitoring of vessel movements and fishing activities, ensuring compliance with regulations and preventing overfishing (Pierre *et al.*, 2024). Blockchain technology ensures secure and transparent data storage, fostering trust among stakeholders and facilitating traceability across the value chain. These features make e-PIT adaptable to diverse socio-economic contexts, particularly in regions where trust deficits and resource constraints hinder effective fisheries governance (Alonge *et al.*, 2024).

The experience of Timor-Leste with its "Peskas" system provides a complementary example of how digital tools can be scaled to improve fisheries management. Peskas collects real-time data from small-scale fishers using mobile technologies and community-based enumerators, covering approximately 20% of the country's coastal fishing areas. Its adoption as the official monitoring system catalyzed greater collaboration between government agencies and fishing communities while attracting new investments into the sector. This demonstrates that even low-cost systems like Peskas or e-PIT can generate a significant impact when paired with capacity-building initiatives and institutional support (Lam *et al.*, 2024).

3.2.5 Recommendations for e-PIT optimization

The implementation of e-PIT has revolutionized fisheries governance in Indonesia, demonstrating significant improvements in data accuracy, operational efficiency, and revenue transparency within a relatively short period. Between 2022 and 2024, the record of vessel arrivals surged by 475% reported catch doubled from 555.2 million kilograms in 2023 to 1.167 billion kilograms in 2024, and PHP revenue rose by 161%, ~~to~~ reaching Rp 951.64 billion in 2024. These advancements validate e-PIT's scalability and its potential as a replicable digital governance model for other developing nations aiming to modernize their fisheries management system.

However, it is important to note that this study primarily focuses on the short to medium term impacts of e-PIT's implementation. While the results are promising, they do not fully capture the long term sustainability of the system. Sustained success will require continuous improvements and adaptive governance strategies to respond to evolving environmental, technological, and institutional challenges. Key short-term challenges that must be addressed include cybersecurity vulnerabilities, uneven digital infrastructure, and limited stakeholder digital literacy.

To ensure long-term resilience, future research should explore the durability of institutional reforms enabled by e-PIT, the system's adaptability to emerging threats such as climate change and shifting marine ecosystems, and its integration with broader marine spatial planning and conservation initiatives. Additionally, longitudinal studies are needed to assess whether performance gains are maintained over time and how the platform influences socio-economic outcomes for coastal communities.

Recommendations for strengthening long - term sustainability include optimizing and decentralizing digital infrastructure, embedding adaptive cybersecurity protocols, fostering inclusive stakeholder participation, and developing a comprehensive monitoring and evaluation framework that includes ecological, economic, and social performance metrics. By implementing these measures and continuing research beyond the 2024 horizon, e-PIT can evolve into a durable instrument of sustainable fisheries governance, aligning with international standards such as the FAO Code of Conduct and SDG 14, while contributing to broader ocean stewardship and food security goals.

4. Conclusion

e-PIT has proven to be a transformative tool for fisheries governance, enhancing operational efficiency, data accuracy, and financial transparency. Its scalability and adaptability position it as a replicable model for digital governance in developing nations. However, addressing security vulnerabilities, expanding infrastructure, and conducting longitudinal studies will be crucial to ensuring its sustained success and broader applicability. By aligning with global frameworks like the FAO Fisheries Governance Framework and SDG 14, e-PIT contributes to the modernization and sustainability of fisheries management worldwide.

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Authors' Contributions

All authors have contributed to the final man-

uscript. The contribution of each author is as follows: A.S. conceptualized the study, designed the methodology, and wrote the manuscript. H.N.H. and R.T.A. collected and analyzed the data and reviewed the manuscript. R.R.T. contributed to the methodology and data interpretation. Y.H. participated in data collection and manuscript editing. F.U. helped with the research design and manuscript revision. F.S. critically reviewed the manuscript. P.K. contributed to the research methodology, data analysis, and provided feedback on the manuscript.

Conflict of Interest

The authors declare that they have no competing interests.

Declaration of Artificial Intelligence (AI)

The author acknowledges using an AI such as Grammarly, Consensus, and ChatGPT to improve all grammar in this article, from the Abstract to the Conclusion. All AI-generated content was rigorously reviewed, edited, and validated to ensure accuracy and authenticity. Turnitin is also used to reduce high plagiarism rates. Full responsibility for the final content of the manuscript rests with the authors. A comprehensive description of the tool's application was tailored to the publisher's ethical guidelines to ensure transparency and support the review process.

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