

Liquidity Dominance and Nonlinear Stability Dynamics in Indonesian Islamic Banking Using Artificial Neural Networks

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Abstract

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Purpose—This study aims to examine the non-linear relationship between operational efficiency, profitability, and financing risk in Indonesian Islamic commercial banks, while developing predictive models for systemic risk and identifying key determinants of financial instability.

Design/methodology/approach—The study adopts a quantitative explanatory approach, integrating descriptive statistics and Pearson correlation with Artificial Neural Networks (ANN) and Recurrent Neural Networks (RNN) to capture complex non-linear relationships. Model interpretability is enhanced using SHapley Additive exPlanations (SHAP) to assess the relative importance of predictors.

Findings—The findings reveal that the relationship between operational efficiency and financing risk is inherently non-linear, characterized by a critical threshold beyond which efficiency improvements increase NPF. The ANN model demonstrates high predictive accuracy, confirming its effectiveness as an early warning system. Furthermore, liquidity conditions, represented by FDR, emerge as the dominant driver of systemic risk, supporting the Bad Luck hypothesis over the Bad Management hypothesis.

Originality/value—This study introduces the concept of the Digital Efficiency Stability Threshold, which redefines efficiency as a bounded construct within Islamic banking. It also integrates machine learning and explainable AI into the analysis of financial stability, bridging the gap between predictive performance and interpretability.

Research limitation and implication—The study is limited to a short observation period and a single-country context. Future research should incorporate longer time horizons, cross-country data, and additional macroeconomic variables to enhance generalizability and robustness.

Keywords: Islamic banking, financing risk, liquidity, artificial neural network, early warning system

JEL Classifications: G21, G32, C45, C53



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1. Introduction

The Islamic banking industry plays a pivotal role in promoting financial system stability while simultaneously advancing equitable and sustainable economic development (Saleem et al., 2021; Rahma & Elfaki, 2025; Hanif et al., 2024). In the Indonesian context, Islamic Commercial Banks (ICBs) function not only as Sharia-compliant financial intermediaries but also as strategic instruments for strengthening national economic resilience, particularly in the face of increasing macroeconomic volatility and rapid digital transformation within the financial sector (Menne et al., 2023; Rokhlinasari et al., 2025; Mutia et al., 2025).

Despite their strategic importance, Islamic banks continue to face substantial structural challenges, particularly in terms of operational efficiency and financing stability (Meero, 2025; Parsa, 2020; Ghroubi & Khalifa, 2025). The persistently high Operating Expenses to Operating Income ratio (BOPO) observed in several ICBs reflects inefficiencies in internal operations, while the upward trend in Non-Performing Financing (NPF) indicates growing exposure to systemic risk (Rahmadani, 2025; Hartanto et al., 2023; Harizanto, 2020). Importantly, the interaction between efficiency and financing risk is neither linear nor static; instead, it evolves dynamically in response to structural changes, technological adoption, and external economic shocks (Maulana et al., 2025; Sajid et al., 2023; Jouini et al., 2025).

Conventional linear econometric approaches often fail to adequately capture such complexity. These models typically assume proportional and homogeneous relationships, thereby limiting their ability to identify threshold effects and dynamic interactions among financial variables. Consequently, the adoption of machine learning techniques, particularly Artificial Neural Networks (ANN) and Recurrent Neural Networks (RNN), has become increasingly relevant for uncovering hidden, non-linear patterns in financial systems (Tu et al., 2025; Polyzos et al., 2022; Gafsi, 2025).

Although Indonesia's Islamic banking sector has experienced steady growth in assets and financing activities, concerns regarding financing quality persist (Fakhrunnas et al., 2022; Sari et al., 2024; Mawardi et al., 2024). Fluctuations in NPF suggest the presence of underlying vulnerabilities that remain insufficiently understood (Saliba et al., 2023; Peykani et al., 2025; Sewanyina et al., 2025). In particular, there is limited empirical evidence on how non-linear relationships emerge among operational efficiency (BOPO), profitability (Net Operating Margin/NOM), and financing risk (NPF). Furthermore, the relative roles of internal inefficiency (bad management) versus external shocks (bad luck) in shaping financing instability remain underexplored. The effectiveness of capitalization (Capital Adequacy Ratio/CAR) and liquidity management (Financing to Deposit Ratio/FDR) in mitigating these risks also remains inconclusive. The absence of a comprehensive understanding of these interactions may reduce the effectiveness of supervisory frameworks and early warning systems.

A growing body of literature has examined efficiency, stability, and risk in Islamic banking. Mawardi et al. (2024) employ a Markov Switching Dynamic Regression model to analyze banking stability in Indonesia, finding that Islamic banks exhibit higher stability probabilities than conventional banks, albeit with weaker recovery capacity during crises. This finding is reinforced by Mawardi et al. (2025), who highlight the significant role of economic uncertainty, particularly for smaller banks. However, these studies primarily focus on regime classification rather than continuous risk prediction.

At the micro level, [Hartanto et al. \(2023\)](#) investigate the determinants of NPF using a dynamic panel Generalized Method of Moments (GMM) approach, emphasizing the importance of internal performance factors such as efficiency and profitability. Nevertheless, their linear framework limits the ability to capture complex interactions and non-linear thresholds. [Fakhrunnas & Anto \(2023\)](#) address this limitation by employing a Nonlinear Autoregressive Distributed Lag (NARDL) model, demonstrating asymmetric effects of Islamic financing on financial stability. However, their analysis remains at the macro level and does not explicitly explore bank-level internal dynamics.

Efficiency-focused studies such as [Saâdaoui & Khalfi \(2022\)](#), [Sukmana et al. \(2020\)](#), [Salama \(2022\)](#), and [Parsa \(2020\)](#) utilize methods such as MARS and DEA to evaluate banking efficiency. While these studies successfully capture efficiency performance, they tend to treat efficiency as an objective rather than a potential source of risk when exceeding optimal levels. Similarly, [Jusni et al. \(2019\)](#) examine the relationships among BOPO, NPF, and NOM, but their analysis remains confined to linear relationships and short-term dynamics.

From an institutional perspective, [Safiullah \(2021\)](#) and [Safiullah & Shamsuddin \(2019\)](#) highlight the role of Sharia Supervisory Boards in enhancing bank efficiency and stability, while [Trinugroho et al. \(2021\)](#) demonstrate that spin-off policies may increase risk and reduce efficiency. Meanwhile, [Masrizal et al. \(2022\)](#) and [Rizvi et al. \(2020\)](#) emphasize external and structural determinants, including economic freedom and systemic interactions. However, these studies largely overlook the dynamic interplay of internal financial variables. [Athief et al. \(2025\)](#) extend the literature by linking Islamic financing to sectoral economic growth, yet without addressing endogenous risk mechanisms at the bank level.

Overall, prior studies reveal three major gaps. First, the relationship between operational efficiency and financing stability remains inadequately explained, particularly in a non-linear framework. Second, existing research tends to analyze efficiency, liquidity, and risk in isolation rather than as interconnected systems. Third, although several studies have examined efficiency, stability, and financing risk in Islamic banking, most of them rely on conventional econometric approaches such as GMM, DEA, NARDL, and Markov Switching models, which primarily emphasize either prediction or efficiency measurement separately. Empirical studies integrating Artificial Neural Networks (ANN), Recurrent Neural Networks (RNN), and explainable AI (SHAP) within a unified framework for Islamic banking stability analysis remain very limited, particularly in identifying non-linear efficiency-risk thresholds. Moreover, a comprehensive theoretical framework defining optimal efficiency thresholds consistent with prudential principles and Maqasid al-Shariah is still absent.

To address these gaps, this study adopts a non-linear analytical framework based on Artificial Neural Networks (ANN) and Recurrent Neural Networks (RNN), combined with explainable artificial intelligence techniques. It empirically examines the Bad Management versus Bad Luck hypotheses and introduces a novel concept, namely the Digital Efficiency Stability Threshold, which conceptualizes the optimal boundary between efficiency and stability within a Sharia-compliant financial system.

Methodologically, this study contributes by extending prior Islamic banking stability studies beyond conventional linear and efficiency-based models through the integration of ANN, RNN, and SHAP. This framework enables simultaneous prediction, dynamic pattern recognition, and model interpretability in examining the interactions among BOPO, NOM,

CAR, FDR, and NPF. Conceptually, it advances the literature by redefining efficiency as a bounded construct rather than a monotonic objective. Practically, it provides a foundation for developing more adaptive early warning systems for regulators and Islamic banking practitioners.

The primary objective of this study is to identify non-linear relationships among operational efficiency, profitability, and financing risk in Indonesian Islamic banks. It further aims to develop predictive models for systemic risk, evaluate the relative importance of key financial variables using SHAP analysis, and formulate a theoretical framework that integrates digital efficiency, financial stability, and Maqasid al-Shariah principles.

By integrating advanced analytics with Islamic economic values, this study is expected to provide both academic and policy-relevant contributions toward strengthening the resilience and sustainability of the Islamic banking system in Indonesia.

2. Literature Review

2.1 Theoretical Background

The relationship between operational efficiency, financial stability, and risk in banking institutions can be understood through several complementary theoretical perspectives. First, the efficiency–risk hypothesis posits that inefficiencies in bank operations increase the likelihood of financial distress, as higher operating costs reduce monitoring effectiveness and weaken risk management capacity. This perspective aligns with the Bad Management hypothesis, which argues that poor managerial quality is a primary driver of non-performing financing (NPF). Conversely, the Bad Luck hypothesis attributes financial instability to exogenous shocks, suggesting that increases in problematic financing may arise independently of managerial performance.

These competing hypotheses are closely linked to the broader framework of banking stability theory, where the interaction between profitability, liquidity, and capitalization determines the resilience of financial institutions. From this perspective, the Capital Adequacy Ratio (CAR) functions as a buffer against unexpected losses, while the Financing to Deposit Ratio (FDR) reflects liquidity risk and financing aggressiveness. Operational efficiency in Islamic banking reflects the bank's ability to manage operating costs while maintaining financing quality and financial sustainability. In this study, operational efficiency is proxied by the Operating Expenses to Operating Income ratio (BOPO), which conceptually represents cost management effectiveness and its potential implications for financing risk and profitability.

In the context of Islamic banking, these relationships are further shaped by the principles of Maqasid al-Shariah, particularly the objective of *hifz al-mal* (protection of wealth). Unlike conventional banking, efficiency in Islamic financial institutions is not solely evaluated in terms of cost minimization but must also align with prudential principles, fairness, and long-term stability. This introduces the notion that efficiency may have an optimal boundary, beyond which excessive cost-cutting or aggressive financing strategies could undermine financial stability.

To capture such complexity, recent advancements in non-linear systems theory and machine learning provide a more appropriate analytical foundation. Artificial Neural Networks (ANN) and Recurrent Neural Networks (RNN) are particularly relevant, as they

allow for the modeling of non-linear interactions, threshold effects, and dynamic trajectories that cannot be captured by traditional linear econometric models. Furthermore, the integration of Explainable Artificial Intelligence (XAI), such as SHapley Additive exPlanations (SHAP), enables the interpretation of complex models, thereby addressing the trade-off between predictive accuracy and transparency in financial analysis.

Taken together, these theoretical perspectives suggest that the relationship between efficiency, liquidity, and financing risk is inherently non-linear, dynamic, and context-dependent. This study builds upon these foundations by proposing a conceptual extension in the form of a Digital Efficiency Stability Threshold, which defines the optimal level of efficiency that remains consistent with financial stability and Sharia-compliant values.

2.2 Previous Studies

The empirical literature on Islamic banking has extensively examined the interconnections among efficiency, stability, and financial risk, although often in fragmented ways. A first strand of research focuses on banking stability and systemic dynamics. [Mawardi et al. \(2024\)](#) employ a Markov Switching Dynamic Regression model to analyze stability regimes in Indonesian banking, finding that Islamic banks exhibit higher stability probabilities than conventional banks, albeit with lower recovery capacity during crises. This finding is reinforced by [Mawardi et al. \(2025\)](#), who demonstrate that economic uncertainty significantly affects banking stability, particularly among smaller institutions. However, these studies primarily emphasize regime identification rather than continuous and forward-looking risk prediction.

A second strand examines the determinants of financing risk, particularly NPF. [Hartanto et al. \(2023\)](#) utilize a dynamic panel Generalized Method of Moments (GMM) approach and find that internal factors, such as efficiency and profitability, play a crucial role in mitigating financing risk. While this supports the Bad Management hypothesis, the linear nature of the model constrains its ability to capture non-linear interactions and threshold effects. [Fakhrunnas & Anto \(2023\)](#) address this limitation by applying a Nonlinear Autoregressive Distributed Lag (NARDL) model, revealing asymmetric relationships between Islamic financing and financial stability. Nevertheless, their analysis remains at the macro level and does not explicitly investigate bank-level internal mechanisms.

A third stream of literature focuses on efficiency measurement and performance evaluation. [Saâdaoui & Khalfi \(2022\)](#) employ Multivariate Adaptive Regression Splines (MARS) to assess Islamic banking efficiency across countries, highlighting the importance of governance and macroeconomic conditions. Similarly, [Sukmana et al. \(2020\)](#), [Salama \(2022\)](#), and [Parsa \(2020\)](#) apply Data Envelopment Analysis (DEA) and meta-frontier approaches to evaluate efficiency and technological gaps. While these studies provide valuable insights into efficiency performance, they predominantly treat efficiency as an end goal rather than as a potential source of systemic risk.

At a more micro-operational level, [Jusni et al. \(2019\)](#) examine the relationships among BOPO, NPF, and Net Operating Margin (NOM), finding that efficiency and financing risk directly influence profitability. However, their findings are based on linear relationships and do not capture long-term or non-linear dynamics. From a governance perspective, [Safiullah \(2021\)](#) and [Safiullah & Shamsuddin \(2019\)](#) emphasize the role of Sharia Supervisory Boards in enhancing efficiency and stability, while [Trinugroho et al. \(2021\)](#)

show that spin-off policies may increase financing risk and reduce efficiency in the medium term.

Other studies highlight external and structural determinants. [Masrizal et al. \(2022\)](#) find that economic freedom positively influences the efficiency of Islamic rural banks, while [Rizvi et al. \(2020\)](#) demonstrate that Islamic banks contribute to systemic stability through asset and liability channels. [Athief et al. \(2025\)](#) further extend this literature by linking Islamic financing and NPF to sectoral economic growth. However, these studies primarily focus on macro-level or institutional factors and do not sufficiently explore internal dynamic interactions among financial ratios.

Overall, prior studies consistently acknowledge the importance of efficiency, liquidity, and profitability in shaping Islamic banking stability. However, the literature remains fragmented, as most studies examine these variables separately using conventional linear approaches, thereby limiting the ability to explain dynamic interactions, threshold effects, and systemic risk trajectories.

However, several unresolved issues remain. The literature has yet to fully explain the non-linear relationship between efficiency and financing risk, particularly in identifying threshold effects. Moreover, most studies analyze efficiency, liquidity, and risk in isolation rather than as an integrated system. Finally, there is a notable absence of machine learning-based approaches that can simultaneously provide predictive accuracy and interpretability in mapping financial risk dynamics.

3. Methodology

The data employed in this study consist of secondary monthly time-series data obtained from publicly available financial reports of Islamic banking institutions in Indonesia, covering the period from January 2024 to January 2025. The use of high-frequency monthly observations enables the analysis to capture short-term dynamics and rapid adjustments in financial indicators, which are particularly relevant in the context of ongoing digital transformation and evolving financial conditions in the Islamic banking sector. This period is considered analytically meaningful, as it reflects recent structural adjustments and post-digitalization dynamics within the industry.

Although the observation period is relatively short, the use of monthly high-frequency data allows the model to capture short-term fluctuations and dynamic interactions among financial variables more effectively. Nevertheless, the study acknowledges that a longer observation horizon may further strengthen the robustness and generalizability of the machine learning results.

Methodologically, this study adopts a machine learning-based approach, specifically Artificial Neural Networks (ANN), which is well suited for modeling complex, non-linear relationships and interaction effects among financial variables. Unlike conventional linear econometric models, ANN does not impose strict distributional assumptions and is capable of extracting meaningful patterns from relatively concise datasets, particularly when the objective is predictive modeling and pattern identification ([Tu et al., 2025](#); [Polyzos et al., 2022](#); [Gafsi, 2025](#)).

Furthermore, the primary focus of this study is not on statistical generalization but on uncovering underlying behavioral patterns and dynamic interactions among key financial ratios. Therefore, the dataset is considered appropriate for capturing the structural

relationships between operational efficiency, liquidity, profitability, and financing risk within the specified context. The research variables include the Capital Adequacy Ratio (CAR), Return on Assets (ROA), Non-Performing Financing (NPF), Financing to Deposit Ratio (FDR), Operating Expenses to Operating Income ratio (BOPO), and Net Operating Margin (NOM).

In this study, CAR is measured as the ratio of bank capital to risk-weighted assets, reflecting financial resilience against unexpected losses. ROA is measured by net income relative to total assets, representing profitability performance. NPF is calculated as the proportion of problematic financing to total financing, indicating financing risk. FDR measures the proportion of financing distributed relative to third-party funds, reflecting liquidity management behavior. BOPO represents operational efficiency through the ratio of operating expenses to operating income, while NOM measures the bank's ability to generate operating margins from productive assets.

Data analysis is conducted through three main stages. The first stage involves descriptive statistical analysis, encompassing measures of central tendency (mean and median), dispersion (standard deviation), and higher-order distributional measures, namely skewness and kurtosis. This analysis aims to identify the distributional characteristics of the data, the stability of financial ratios, and the potential presence of extreme events that are relevant in the context of Islamic banking risk.

The second stage involves Pearson correlation analysis to identify the direction and strength of linear relationships among the key variables, particularly between operational efficiency (BOPO), financing risk (NPF), and profitability performance (NOM). The Pearson correlation coefficient is formally expressed as:

$$r_{xy} = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \quad (1)$$

The third stage constitutes the core analysis, employing a machine learning approach based on Artificial Neural Networks (ANN) to capture non-linear relationships and complex interactions among financial variables. Conceptually, the ANN function can be expressed as:

$$\hat{y} = f\left(\sum_{i=1}^n w_i x_i + b\right) \quad (2)$$

Where x_i represents the input variables (CAR, ROA, FDR, BOPO, and NOM), w_i denotes the network weights, b is the bias term, and f refers to a non-linear activation function. The ANN model is trained using the backpropagation algorithm with the objective of minimizing a loss function specified as the Mean Squared Error (MSE), which is defined as:

$$MSE = \frac{1}{n} \sum_{i=1}^n (y_i - \bar{y}_i)^2 \quad (3)$$

The ANN architecture employed in this study consists of an input layer representing the financial ratios, one hidden layer with non-linear activation functions, and an output layer predicting financing risk dynamics. The model training process applies backpropagation optimization with iterative learning to minimize prediction error. To improve robustness, the dataset was divided into training and testing subsets, and model performance was evaluated using Mean Squared Error (MSE) and Mean Absolute Error (MAE). In addition, explainable AI through SHAP analysis was implemented to interpret the relative contribution of each predictor variable to the model output.

To enhance model interpretability, this study adopts an explainable artificial intelligence (XAI) approach through feature importance and partial dependence analyses. This approach enables the identification of the relative contributions of individual financial variables to changes in financing risk (Non-Performing Financing/NPF) and operational margin (Net Operating Margin/NOM), thereby ensuring that the analytical results are not merely predictive in nature but also inferential and directly relevant for policy-oriented decision making.

4. Results and Discussion

4.1 Results

The distribution of financial ratio values is visualized using boxplots in Figure 1 to identify central tendency (median), data dispersion, and the presence of outliers. The visualization results indicate that the Capital Adequacy Ratio (CAR) exhibits a relatively stable median in the range of 25–26 percent with a narrow interquartile range, suggesting consistent capital resilience among Islamic banks throughout the observation period. Return on Assets (ROA) displays greater variability than CAR, reflecting fluctuations in profitability levels driven by dynamics in operating costs and financing margins. Non-Performing Financing (NPF) remains within a relatively controlled range of approximately 2.0–2.15 percent; however, it shows noticeable variation, indicating the potential emergence of heightened risk during certain periods. The Financing to Deposit Ratio (FDR) demonstrates a relatively wide data dispersion, signaling volatility in financing allocation policies and liquidity management practices. Meanwhile, the Operating Expenses to Operating Income ratio (BOPO) exhibits higher variability compared to CAR and ROA, indicating heterogeneity in operational efficiency across periods. The Net Operating Margin (NOM) remains relatively stable, although minor fluctuations are observed, reflecting the sensitivity of margins to changes in market conditions. Differences between mean and median values in several ratios particularly BOPO and FDR suggest skewed data distributions, thereby warranting careful consideration of normality assumptions in subsequent analyses.

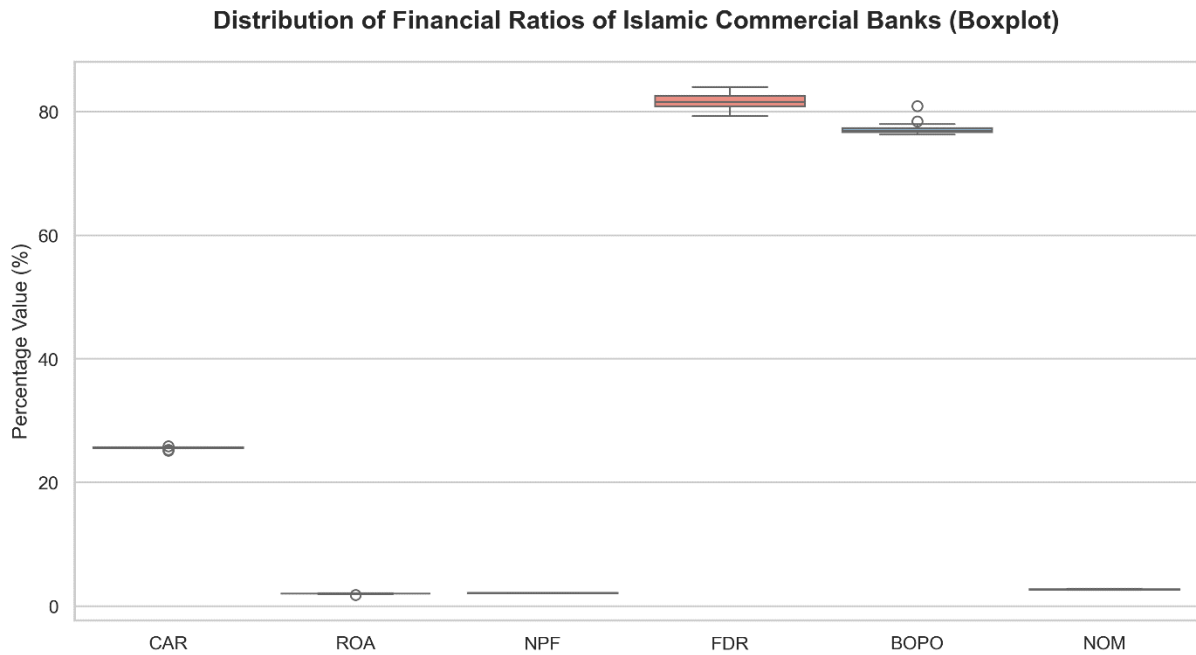


Figure 1. Distribution of financial ratio values

Source: Output Python, 2026

The histogram and Kernel Density Estimation (KDE) visualizations presented in Figure 2 reveal several notable distributional characteristics. First, the distribution of Non-Performing Financing (NPF) exhibits a pronounced right skewness, indicating the presence of specific months characterized by spikes in financing risk that exceed normal conditions. In the context of Islamic economics, this phenomenon is particularly relevant, as it may reflect periods of external stress or shortcomings in financing selection and screening processes.

Second, the Operating Expenses to Operating Income ratio (BOPO) also demonstrates a tendency toward positive skewness, suggesting that increases in operational inefficiency occur sporadically but exert a disproportionately large impact. Finally, the distribution of the Financing to Deposit Ratio (FDR) displays fat tails, indicating the potential occurrence of extreme events associated with liquidity stress. From a kurtosis perspective, the presence of heavy tails in both NPF and FDR implies that, although extreme events are relatively infrequent, their effects on the stability of the Islamic banking system can be substantial. These findings underscore the importance of early warning systems that are sensitive to rare but systemically consequential events.

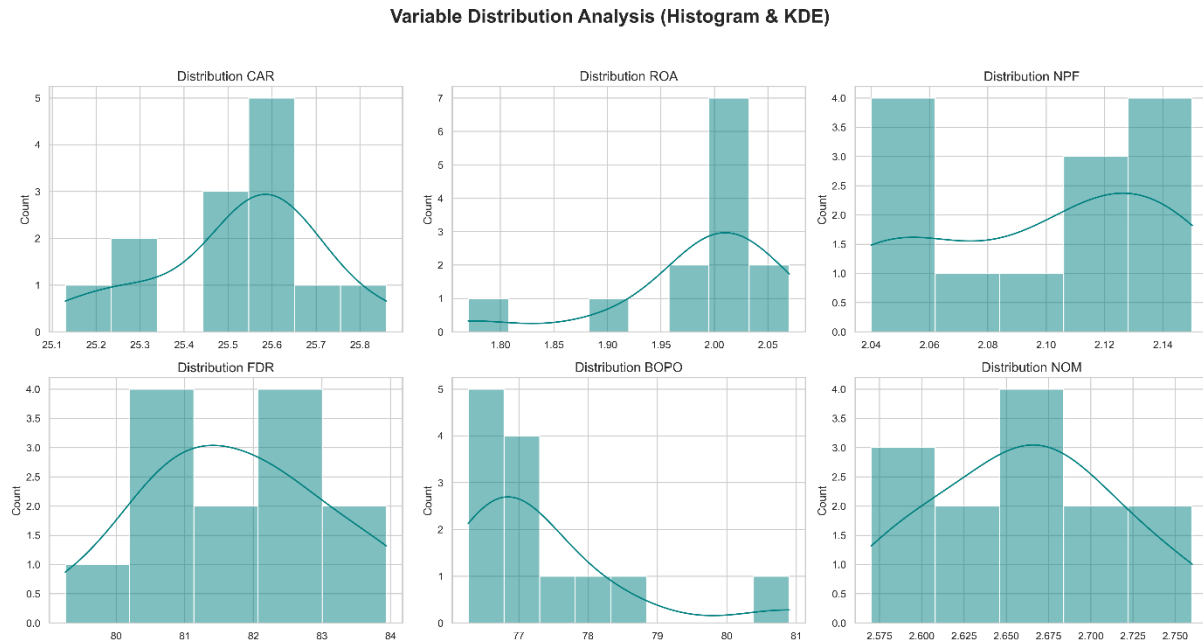


Figure 2. Histogram analysis and Kernel Density Estimation (KDE)

Source: Output Python, 2026

Linear relationships among the variables are examined using a correlation heatmap presented in Figure 3, with the objective of addressing fundamental questions regarding the interconnections among operational efficiency, liquidity, profitability, and financing risk in Islamic banking. The results reveal a relatively strong positive correlation between Non-Performing Financing (NPF) and the Financing to Deposit Ratio (FDR), indicating that increased aggressiveness in financing disbursement tends to be accompanied by a higher incidence of problematic financing. In addition, the correlation between the Operating Expenses to Operating Income ratio (BOPO) and Return on Assets (ROA) is strongly negative, empirically confirming that operational inefficiency exerts a direct adverse effect on profitability.

Meanwhile, the linear relationship between BOPO and NPF is relatively weak, suggesting that increases in operational inefficiency do not necessarily translate immediately into higher financing risk in the short run. On the other hand, the negative correlation between the Capital Adequacy Ratio (CAR) and NPF points to the protective role of capitalization in mitigating financing risk, albeit with limited strength. Overall, these findings provide preliminary evidence that the relationship between operational efficiency and financing risk is not entirely linear, thereby necessitating the application of non-linear and multivariate approaches in subsequent stages of analysis.

The first evaluation in this study focuses on assessing the accuracy of artificial intelligence-based models in predicting the trajectory of problematic financing risk, measured by Non-Performing Financing (NPF), in Indonesian Islamic commercial banks. Figure 1 presents a comparison between actual NPF values and the predictions generated by the Artificial Neural Network (ANN) model within an early warning system framework.

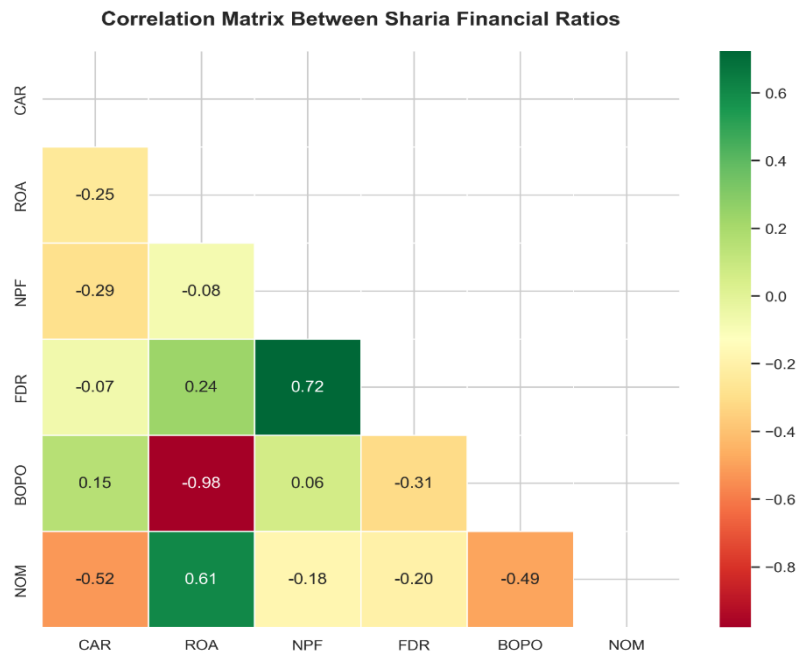


Figure 3. Linear relationship matrix between variables
Source: Output Python, 2026

Figure 4 shows that the AI-based prediction closely follows the actual NPF trajectory, indicating strong predictive accuracy. This result is supported by a low Mean Absolute Error (MAE) of approximately 0.03%, confirming the model's effectiveness in capturing financing risk dynamics.

These findings empirically address the second research objective (the predictive objective), demonstrating that an ANN-based machine learning approach is well suited for predicting systemic risk in Islamic banking. In other words, the model is not only statistically well-fitted but also practically relevant as an early warning system for both regulators and Islamic bank management

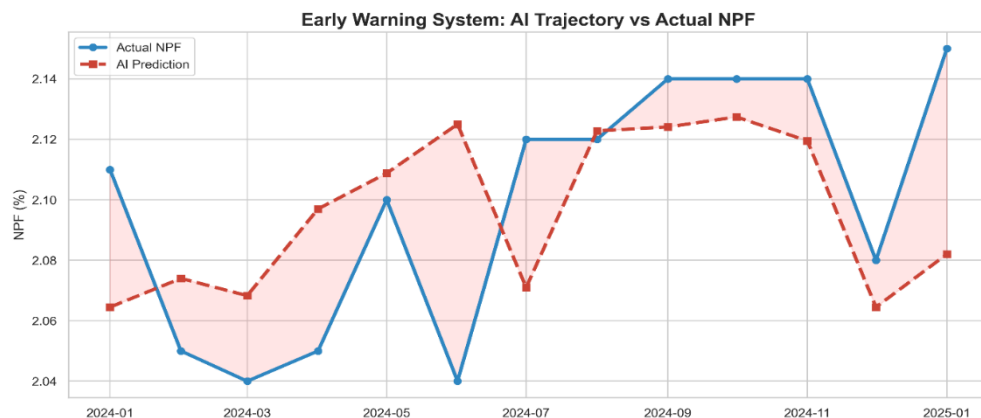


Figure 4. Early Warning System: AI Trajectory vs Actual NPF
Source: Output Python, 2026

The subsequent analysis is directed toward identifying the relationship patterns between operational efficiency, as represented by the Operating Expenses to Operating Income ratio (BOPO), and the level of financing risk measured by Non-Performing Financing (NPF). Figure 5 illustrates this relationship through a scatter plot accompanied by a non-linear curve generated from the AI-based model.

As shown in Figure 5, the relationship between BOPO and NPF is inherently non-linear. At certain levels of BOPO, improvements in operational efficiency are not necessarily followed by a reduction in NPF. Instead, the curve exhibits an inflection point, indicating that beyond a specific threshold, further increases in BOPO are associated with a sharper rise in NPF.

These findings confirm that the relationship between operational efficiency and financing risk does not follow a constant proportional pattern. Moderate efficiency improvements may initially support stability, but excessive efficiency pressure particularly through aggressive cost reduction and financing expansion tends to increase financing risk after a critical threshold is reached. Accordingly, the first research objective (Identification of Non-Linear Patterns) is achieved, as this study successfully reveals the presence of a critical efficiency threshold that has the potential to trigger financing instability. This pattern also indicates the existence of an optimal efficiency threshold, beyond which excessive cost reduction may increase financing risk.

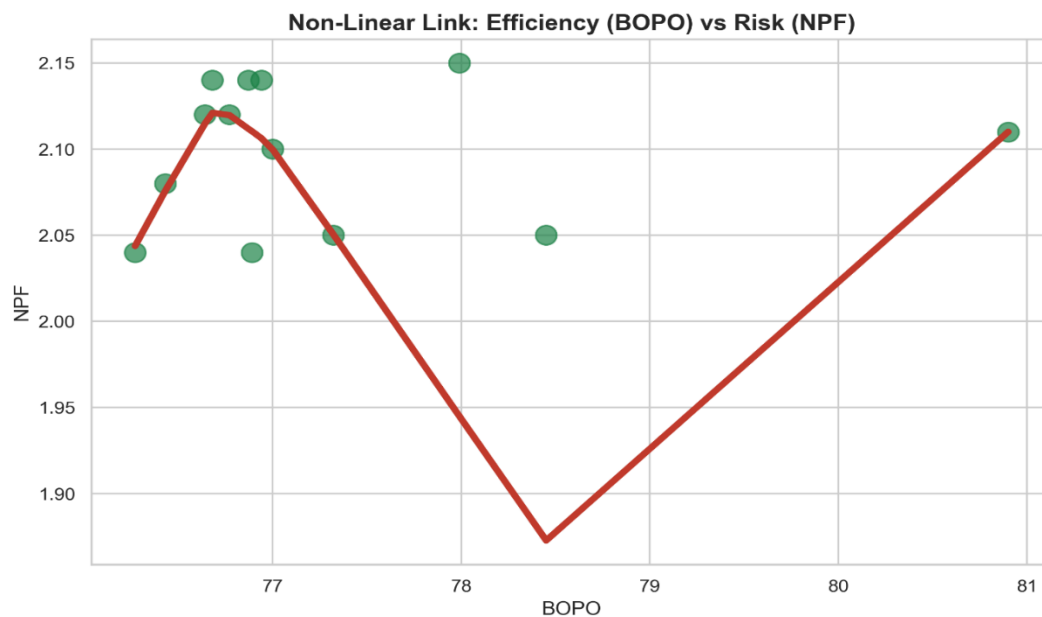


Figure 5. Non-Linear Link: Efficiency (BOPO) vs Risk (NPF)

Source: Output Python, 2026

To test the validity of the Bad Management versus Bad Luck hypotheses, this study does not rely solely on the bivariate relationship between BOPO and NPF. Instead, it simultaneously analyzes the relative contributions of multiple financial ratios using an explainable machine learning (XAI) approach.

The SHAP-based feature importance visualization is presented in Figure 6. The key finding indicates that the Financing to Deposit Ratio (FDR) exerts the most dominant contribution to systemic risk, with an approximate weight of 54 percent, substantially

exceeding the contributions of BOPO, the Capital Adequacy Ratio (CAR), and the Net Operating Margin (NOM).

The dominance of FDR as the primary risk driver suggests that liquidity pressures and financing market conditions play a more substantial role in driving increases in NPF than managerial inefficiency alone. Accordingly, in the empirical context of Indonesian Islamic banking in 2024, the Bad Luck hypothesis representing external shocks and liquidity stress receives stronger support than the Bad Management hypothesis.

These findings directly address the third research objective (Theory Testing) while simultaneously offering a nuanced contribution to the Islamic banking literature, which has traditionally emphasized internal efficiency as the principal determinant of financing risk.

The feature importance analysis depicted in Figure 6 also provides a more granular understanding of the role of individual financial ratios in sustaining the stability of the Islamic banking system. Although BOPO continues to contribute to risk, its relative weight is considerably smaller than that of FDR and even ROA.

These results imply that strengthening capitalization (CAR) and improving operational efficiency alone are insufficient to ensure systemic stability if liquidity management is not conducted optimally. In other words, the stability of Islamic banking in Indonesia appears to be more sensitive to the dynamics of financing disbursement and funding structures than to operational cost efficiency.

Collectively, these findings comprehensively address the fourth research objective (Feature Importance) and reinforce the argument that supervisory frameworks for Islamic banking should place liquidity risk at the core of macroprudential policy design.

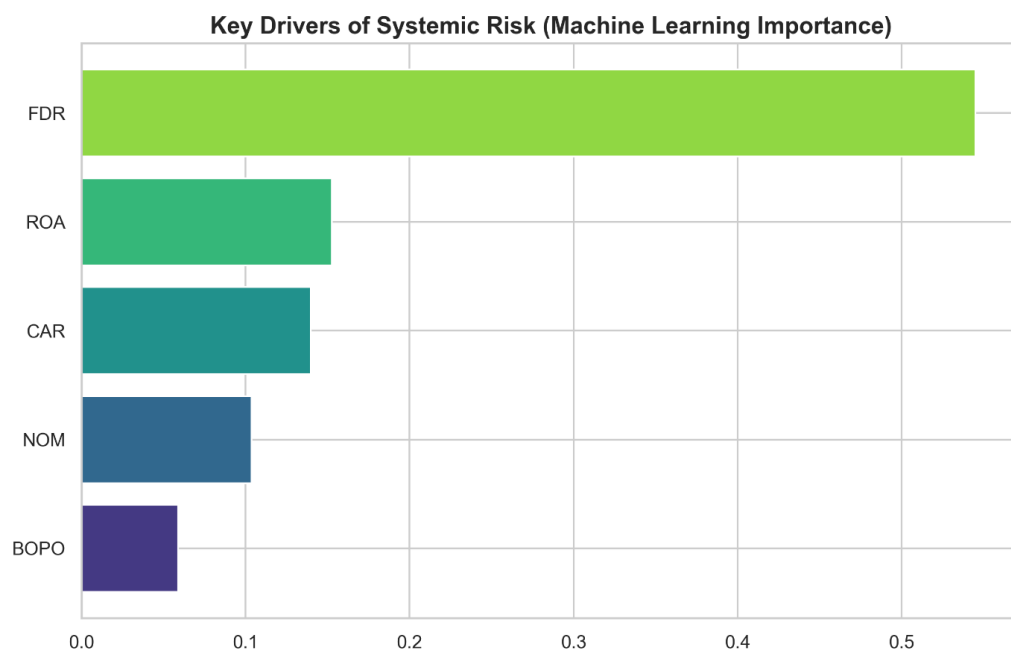


Figure 6. Key Drivers of Systemic Risk

Source: Output Phyton, 2026

Based on the non-linear pattern illustrated in Figure 5, this study identifies a specific BOPO point at which Non-Performing Financing (NPF) begins to increase disproportionately. This point is proposed as the Digital Efficiency Stability Threshold, defined as the level of operational efficiency that remains consistent with financing stability.

This concept constitutes the study's primary theoretical contribution, as it offers a novel perspective that digital efficiency in Islamic banking is not monotonically beneficial. Efficiency gains beyond a certain threshold may instead generate risk pressures, particularly when they are not accompanied by prudent liquidity management aligned with the principles of Maqasid al-Shariah.

Accordingly, one of the research objective (New Theoretical Insight) is achieved through the formulation of this concept, which underscores that the stability of Islamic banking in Indonesia is determined more by the balance among efficiency, liquidity, and prudential considerations than by cost efficiency alone.

4.2 Discussion

The results of the descriptive and exploratory analyses indicate that the operational efficiency ratio (BOPO) and the Net Operating Margin (NOM) exhibit distributional patterns that are not fully symmetric and display clear indications of skewness and kurtosis. These findings indicate periods of high cost pressure and margin fluctuation that may increase financing risk, suggesting that Islamic banking dynamics cannot be fully explained by linear approaches. Accordingly, the study's first research objective identifying non-linear patterns among BOPO, NOM, and NPF can be considered achieved. These results are consistent with [Fakhrunnas & Anto \(2023\)](#), who document non-linear and asymmetric relationships in the contribution of Islamic banking to financial stability, while extending this evidence to the micro-level of banks through internal operational ratios.

Furthermore, the relatively weak to moderate linear correlation between BOPO and NPF indicates that the relationship between efficiency and risk is neither proportional nor constant. Under certain conditions, improvements in cost efficiency do not automatically reduce financing risk and may even exacerbate NPF when efficiency gains are achieved through tighter monitoring expenditures or aggressive financing expansion. This phenomenon provides strong justification for the use of Artificial Neural Networks (ANNs) and Recurrent Neural Networks (RNNs), in line with the predictive objective of this study. The machine learning models developed are shown to effectively map the dynamic trajectories of risk based on the combined effects of CAR, BOPO, and FDR, thereby supporting the development of a more adaptive early warning system compared to traditional econometric models. These findings complement the studies of [Mawardi et al. \(2024\)](#) and [Mawardi et al. \(2025\)](#), which emphasize regime identification, by offering a forward-looking and continuous predictive approach.

In the context of theory testing, the findings indicate that both the Bad Management and Bad Luck hypotheses contribute to financing instability; however, liquidity pressure and financing aggressiveness represented by FDR appear to exert a more dominant influence than operational inefficiency alone. Therefore, the empirical evidence provides relatively stronger support for the Bad Luck hypothesis in the context of Indonesian Islamic banking during the observation period. The non-linear contribution of BOPO to financing risk underscores that internal inefficiencies and the quality of operational management play a more substantial role than external factors alone. This result is consistent with

[Hartanto et al., \(2023\)](#), who highlight the importance of internal performance in mitigating NPF, while extending their findings by demonstrating that the effects of inefficiency are dynamic and non-linear. Accordingly, this study reinforces the argument that the stability of Islamic banking is largely determined by the quality of internal management rather than macroeconomic conditions alone.

The variable contribution analysis using the SHAP approach yields an important finding that BOPO and FDR emerge as the primary drivers of systemic instability, while CAR functions as a conditional buffering factor. Strong capitalization does not necessarily offset the adverse effects of operational inefficiency and liquidity pressure when these two variables move beyond their optimal ranges. This finding extends the results of [Safiullah \(2021\)](#) and [Safiullah & Shamsuddin \(2019\)](#), who emphasize the roles of governance and capital, by demonstrating that the effectiveness of capital is highly contingent upon the quality of operational efficiency and liquidity management. Accordingly, the research objective related to the empirical and interpretative evaluation of key variable contributions to systemic stability has been successfully achieved.

One of the study's principal theoretical contributions is the formulation of the concept of the Digital Efficiency Stability Threshold within the context of Islamic banking. The empirical evidence indicates the existence of a specific cost-efficiency threshold at which digitalization efforts and cost-control strategies remain consistent with prudential principles. However, when efficiency is pushed beyond this threshold, financing risk increases as a result of weakened monitoring functions and deteriorating financing quality. This concept complements the existing literature on Islamic banking efficiency, which has largely focused on cost minimization as the primary objective as reflected in [Saâdaoui & Khalfi \(2022\)](#), [Sukmana et al. \(2020\)](#), and [Parsa, \(2020\)](#) by emphasizing that efficiency possesses an optimal boundary when viewed from the perspectives of financial stability and Maqasid al-Shariah.

From a practical standpoint, the findings provide strategic guidance for Islamic bank management not to regard a low BOPO ratio as the sole indicator of superior performance. Efficiency management should be balanced with sustained investment in financing monitoring systems, human capital quality, and data-driven risk management. For regulators, these findings imply the need to integrate AI-based early warning systems into supervisory frameworks by continuously monitoring liquidity indicators such as FDR and identifying abnormal efficiency-risk patterns in real time. Regulatory authorities may also establish prudential liquidity thresholds and AI-assisted supervisory dashboards to detect potential financing instability at earlier stages. This approach aligns with the recommendations of [Mawardi et al. \(2024\)](#) regarding the strengthening of early warning systems, while offering a more precise and adaptive methodological framework.

Conceptually, this study contributes to the advancement of Islamic economics literature by integrating data science approaches with the normative values of Maqasid al-Shariah in the analysis of financial stability. Stability is not merely understood as financial resilience, but also as the capacity of Islamic banks to sustain their intermediation function in a fair, prudent, and welfare-oriented manner. Accordingly, this research not only enriches the academic discourse on efficiency and risk in Islamic banking but also offers a novel analytical framework that is highly relevant for the development of a stable, inclusive, and sustainable Islamic banking industry in the digital era.

5. Conclusion and Recommendations

This study makes a significant contribution to deepening the understanding of the relationship between operational efficiency and the stability of Islamic banking in Indonesia by adopting a non-linear, artificial intelligence-based approach. Through the application of Artificial Neural Networks and explainable AI techniques, the study demonstrates that the relationships among BOPO, NOM, and NPF are neither linear nor proportional, but instead follow dynamic patterns shaped by complex interactions among cost efficiency, liquidity, and capitalization. These findings advance the Islamic banking literature by extending prior studies that have largely relied on linear and static econometric frameworks. From a theoretical perspective, this research introduces the concept of the Digital Efficiency Stability Threshold, which posits the existence of an optimal efficiency level at which digitalization initiatives and cost-control efforts remain aligned with prudential principles and Maqasid al-Shariah, while potentially exacerbating financing risk once this threshold is exceeded. Accordingly, the study not only enriches academic discourse but also integrates data science perspectives with the normative foundations of Islamic economics in the analysis of financial system stability.

In terms of practical implications, the findings suggest that Islamic bank management should refrain from treating cost efficiency as a singular objective, and instead manage it in balance with the quality of financing oversight and liquidity management. For regulators, the findings support the implementation of machine learning-based early warning systems that are capable of identifying liquidity stress, abnormal financing expansion, and efficiency-risk threshold violations in real time. Such systems may assist supervisory authorities in designing more responsive macroprudential interventions and preventive risk mitigation policies for Islamic banks. Nevertheless, this study is subject to several limitations. The analysis is confined to Islamic commercial banks in Indonesia and a relatively short observation period, which may not fully capture long-term economic cycles or cross-country variations. Moreover, external macroeconomic variables and aspects of Shariah governance are not explicitly incorporated into the predictive models. Future research is therefore encouraged to expand the scope of analysis to cross-country datasets, incorporate macroeconomic and institutional variables, and examine alternative machine learning approaches that are more sensitive to long-term temporal dependencies in order to enhance the validity and generalizability of the findings.

Declarations

Authorship

All authors actively participated in the work, have reviewed and approved the final version of the manuscript, and agree to its submission to JBMIB.

Author Contribution Statement

Iman Supriadi conceptualized and designed the study, conducted the data analysis, and drafted the manuscript; Rahma Ulfa Maghfiroh collected and compiled the data and contributed to the interpretation of the results; and Rukhul Abadi critically revised the manuscript and provided substantial academic feedback. All authors read and approved the final manuscript.

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Data Availability Statement

This research relies on secondary data obtained from the official website of the Financial Services Authority (Otoritas Jasa Keuangan/OJK), specifically the banking financial statements published at <https://www.ojk.go.id/id/kanal/perbankan/data-dan-statistik/laporan-keuangan-perbankan/Default.aspx>. The dataset is publicly accessible through the aforementioned official portal, and therefore the data supporting the findings of this study are available from the corresponding source.

Declaration of Interests Statement

The authors declare that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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