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Exploring weak-form efficiency in global Islamic stock markets: evidence from machine learning and wavelet analysis

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Abstract

Purpose – This study aims to comprehensively assess the weak-form efficiency of nine major global Islamic stock indices by employing a combination of advanced machine learning, wavelet coherence (WTC), and Fourier-based econometric methods. The research seeks to reveal both the persistence of market efficiency and the dynamic nature of volatility–return relationships, especially during crisis periods.

Design/methodology/approach – The analysis uses daily data for nine Dow Jones Islamic stock indices across regions (2004–2025). We combine Fourier-ADF unit root tests, MLP-based ANN forecasting, random-walk benchmarks, Fourier Granger causality, and wavelet coherence to assess return predictability and volatility–return dynamics across time–frequency domains. The ANN is a one-hidden-layer MLP (20 ReLU neurons) with a linear output and Adam optimization, trained for 200 epochs (batch size 32). Data are split chronologically into training and test sets (75:25), with tuning within the training sample. Performance is evaluated using RMSE, MAE, and R^2.

Findings – Overall, the results support weak-form efficiency across all indices: neither the econometric tests nor the machine learning models point to persistent abnormal returns. WTC results show that volatility-return linkages become stronger during major crisis periods (2008, 2020, 2022–23), but these effects fade and do not turn into stable predictive power. The ANN model does outperform the random-walk benchmark in out-of-sample forecast errors, and the Diebold-Mariano test confirms that this difference is statistically significant. Still, near-zero and often negative out-of-sample R^2 values show that the improvement remains modest in predictive terms.

Practical implications – For market regulators and investors, the study emphasizes the importance of maintaining transparency, robust information flows, and effective risk management, particularly during periods of heightened market volatility. The dynamic approach can help policymakers design timely interventions and investors develop more informed, long-term strategies, reducing the risk of overreaction to short-lived market shocks.

Originality/value – To the best of our knowledge, this is the first study to combine machine learning and wavelet coherence analysis with Fourier-based causality and unit root tests to evaluate weak-form efficiency in a broad set of global Islamic stock markets. The interdisciplinary approach offers new empirical insights into the

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time-varying efficiency of Islamic financial markets and provides methodological innovations relevant to both academic research and market practice.

Keywords Efficient market hypothesis, Weak-form efficiency, Global Islamic stock markets, Machine learning, Wavelet analysis

Paper type Research article

1. Introduction

Capital markets are institutional arrangements that facilitate matching between borrowers and lenders, thereby helping to convert savings into investment (Khan *et al*., 2011; Trang, 2022). When functioning efficiently, they play important roles in financial markets: they support growth, enhance transparency, increase investor confidence, and help reduce transaction costs (Emenike and Joseph, 2018; Ülev and Selçuk, 2022). Due to this central role, market efficiency remains one of the most debated topics in finance (Awan and Subayyal, 2016; Dias *et al*., 2020).

This idea is examined in the literature in the context of the Efficient Market Hypothesis (EMH). Based on Bachelier's random walk theory and later developed by Samuelson (1965) and Fama (1965, 1970), this theory defines an efficient market as a structure where all available information is fully reflected in prices (Yavrumyan, 2015; Dubey, 2023). Weak-form efficiency, which is particularly critical for stock markets, suggests that past price movements are already integrated into current values. Therefore, it is not possible to systematically predict future returns by looking only at past data (Ikeora *et al*., 2016; Trang, 2022).

This theory becomes even more interesting when Islamic stock markets are considered. Islamic indices are constructed through Sharia screening rules that exclude companies that do not meet activity-based and financial ratio criteria. As a result, these indices differ from traditional indices in terms of leverage, diversification, and sector composition (Sakınç and Sakınç, 2024; Ülev and Selçuk, 2022). Some studies also show that Islamic indices may behave differently during periods of stress, exhibiting lower volatility or different correlation patterns compared to traditional markets (Chazi *et al*., 2023; Tabash *et al*., 2023). The Islamic finance system, notable for these differences, is growing rapidly. Total Islamic financial assets rose from $2.70 trillion in 2020 to $3.88 trillion in 2024, with Islamic fund assets reaching $193.6 billion. Equities constitute the largest share of these assets (Islamic Financial Services Board (IFSB), 2025). Post-COVID evidence also shows strong regional interconnectedness within Islamic equity markets, although the way shocks propagate differs from traditional systems (Rehman *et al*., 2024).

Nevertheless, research on weak-form efficiency in Islamic stock markets is still limited in scope compared to extensive studies on traditional markets (Al-Khazali *et al*., 2016; Mensi *et al*., 2017; Sakınç and Sakınç, 2024). Most of these studies are primarily based on unit root and similar time series tests. While useful, these methods may be less informative in situations commonly seen in long samples when financial series exhibit structural breaks, non-linearities, regime shifts, and crisis-specific volatility and correlation changes (Çevik, 2018; Chazi *et al*., 2023; Rehman *et al*., 2024; Tabash *et al*., 2023).

In this context, this study tests the weak-form EMH for nine Dow Jones Islamic Market indices: DJICA, DJICHKU, DJIJP, DJIMIND, DJIMKW, DJIMTR, IMUS, DJIUK, and DJMY25D. The analysis combines machine learning-based forecasting with wavelet transform coherence (WTC) in a multi-country and multi-index setting. This allows us to assess weak-form efficiency from multiple angles and account for structural changes, nonlinear dynamics, and crisis-period behavior.

The remainder of the paper is organized as follows. Section 2 reviews the literature. Section 3 presents the data. Section 4 explains the methodology. Section 5 reports the findings. Section 6 presents the conclusions.

2. Literature review

A large body of research has examined the random walk hypothesis, or weak-form EMH, in conventional stock markets across developed and emerging economies. By contrast, studies on

Islamic stock markets remain relatively limited. The evidence is also far from uniform. Some studies support weak-form efficiency, others reject it, and some report mixed results across countries, indices, sectors, or sample periods. This pattern appears in both conventional and Islamic markets. For clarity, the literature is reviewed under three headings: studies supporting weak-form EMH in conventional markets, studies rejecting it or reporting mixed evidence, and studies on Islamic markets together with the methodological issues that motivate the present study.

2.1 Studies supporting weak-form EMH in conventional markets

A number of studies in the literature have provided significant evidence consistent with weak-form efficiency in traditional markets. For example, Fattahi (2010) showed that the German DAX index followed a random walk, while Kok and Munir (2015) reached a similar conclusion for financial stocks in Malaysia. Weak-form efficiency has also been reported for specific indices and markets such as Indonesia, Borsa Istanbul, Casablanca, and some developed country ETFs and stock markets (Malini, 2019; Gazel, 2020; Karademir and Evci, 2020; Benthabet and Benthabet, 2023; Özmerdivanlı, 2024). Showalter and Gropp (2019) also present strong evidence of weak-form efficiency in the US market when transaction costs and risk are taken into account.

Some recent studies also approach market efficiency from new methodological angles. Bagwan *et al*. (2025) discuss EMH through fractional difference equations, while Adegboyo and Sarwar (2025) examine volatility dynamics in the Nigerian market using asymmetric GARCH specifications. Although these studies differ in focus, they show that support for weak-form efficiency remains present in parts of the literature, especially when market structure, risk, and model choice are taken into account.

2.2 Studies rejecting or partially supporting weak-form EMH in conventional markets

A second line of research rejects weak-form efficiency or finds only partial support. Early evidence from markets such as Karachi and Ghana suggests that stock prices do not follow a random walk (Ahmad and Erdem, 1996; Frimpong and Oteng-Abayie, 2007). Similar conclusions are reported for India, Nigeria, Tehran, the Gulf region, Jordan, Bangladesh, Tanzania, Türkiye, Vietnam, Nepal, China, and several emerging markets more broadly (Khan *et al*., 2011; Gimba, 2012; Saeedi *et al*., 2014; Raquib and Alom, 2015; Ikeora *et al*., 2016; Awan and Subayyal, 2016; Ogbulu, 2016; Kumar and Jawa, 2017; Pervez *et al*., 2018; Katabi and Raphael, 2018; Hailu and Vural, 2020; Diallo *et al*., 2021; Risal and Koju, 2021; Trang, 2022; Luo *et al*., 2022; Nik and Marko, 2023; Joshi, 2024; El-Diftar, 2024). In these studies, returns often appear to depend on past information, which is inconsistent with weak-form efficiency.

There is also a sizeable group of studies reporting mixed results. Hepsağ and Akçalı (2015) show that efficiency differs across G7 and E7 countries. Khan and Khan (2016) find inefficiency in daily and weekly Pakistani returns but not in monthly returns. Çevik (2018) reports that the BIST-100 is efficient in high-volatility periods but not in low-volatility periods. Other studies show that efficiency changes across crises, recovery periods, development levels, data frequencies, and empirical methods (Marsani *et al*., 2022; Lee and Choi, 2023; Tutar and Dalgar, 2023; Al-wazier, 2024). Taken together, this literature suggests that weak-form efficiency is highly sensitive to market conditions, sample periods, and methodology.

2.3 Studies on Islamic markets and methodological considerations

Research on Islamic stock markets is smaller in volume and still inconclusive. This is important because Islamic financial markets operate under Shariah principles that prohibit interest, excessive uncertainty, and speculative trading. These features may affect how information is incorporated into prices and may also shape volatility, co-movement, and investor behaviour, especially during periods of stress. Related evidence from investor-level and crisis-period studies also suggests that information channels and market responses can change across regimes and horizons (Naveed *et al*., 2020; Naveed and Ali, 2024).

Empirical findings on Islamic equity-market efficiency remain mixed. Al-Khazali *et al*. (2016) argue that conventional indices are generally more efficient than Islamic ones, although Islamic indices may become more efficient during crises. Mensi *et al*. (2017) show that efficiency in Islamic sectoral indices changes over time. Ali *et al*. (2018) report relatively stronger efficiency in Islamic markets from developed and BRICS economies, whereas Bouoiyour *et al*. (2018) find lower efficiency in emerging Islamic markets. Hassan and Ahmad (2020), Khan *et al*. (2021), and Sakınç and Sakınç (2024) report evidence against weak-form efficiency in several Shariah-compliant indices, while Buğan *et al*. (2021) and Ülev and Selçuk (2022) show that results vary across regimes, market groups, and index sets.

Recent studies also point to the value of methods that can capture time variation and crisis-specific dynamics. Ali *et al*. (2022) document pandemic-period co-movements in Islamic and conventional indices using wavelet coherence. Kazak *et al*. (2025b) show that global uncertainty indicators affect Islamic equity indices, although the strength of this effect differs across indicators. More broadly, time-frequency, connectedness, and machine-learning studies in related financial settings show that dependence structures, spillovers, and forecast performance can vary markedly across horizons and market conditions (Ali *et al*., 2024a, b; Aharon *et al*., 2025; Kazak *et al*., 2025a; Naveed *et al*., 2025). This is important because the Islamic-market literature still relies heavily on traditional tools such as unit root, variance ratio, serial correlation, autocorrelation, and runs tests.

Overall, the literature does not offer a clear consensus on weak-form EMH in Islamic stock markets. Results differ across countries, indices, periods, and methods. One reason may be that conventional tests are often not well suited to financial series marked by structural breaks, nonlinearities, and crisis-driven shifts. For this reason, using approaches such as machine learning and wavelet-based analysis may provide a more informative assessment of weak-form efficiency. This is where the present study aims to contribute.

3. Data and basic structure

3.1 Data

This study examines the behavior of nine global Dow Jones Islamic Market Indices DJICA, DJICHKU, DJIJP, DJIMIND, DJIMKW, DJIMTR, IMUS, DJIUK, DJMY25D under the weak-form EMH. All indices used in our study were selected to represent the major Islamic markets across different regions in different regions, and the data were downloaded directly from the S&P Global and Refinitiv Eikon databases and contained no missing observations or transformations, thereby ensuring the full reproducibility of the results. The dataset, obtained from S&P Global and Refinitiv Eikon databases and compiled using daily closing prices, includes the following date ranges for each index: DJICA: 06/2004–04/2025; DJICHKU: 06/2010–04/2025; DJIJP: 05/2004–04/2025; DJIMIND: 10/2010–04/2025; DJIMKW: 01/2008–04/2025; DJIMTR: 12/2004–04/2025; IMUS: 05/2004–04/2025; DJIUK: 05/2004–04/2025; and DJMY25D: 06/2009–04/2025. Daily closing prices were used for all indices. Due to data availability constraints, it was not possible to obtain data earlier than 2004 for any of the indices. However, each index was analyzed separately within its respective data range, enabling a comparative assessment of the activity levels of Islamic capital markets in different regions over time. Detailed information on the variables used is presented in Table 1.

3.2 Study purpose and contribution

This study examines weak-form efficiency in a broad set of Islamic stock indices using a combined empirical framework. Next-day returns are forecast through ANN models and compared with the random walk benchmark, while time-varying dependence is evaluated

Table 1. Description of variables

Notation	Name of variable	Description of measurement	Data source
x1–x6	Lagged Returns (t–6 to t–1)	$r_{t-i} = \ln\left(\frac{P_{t-i}}{P_{t-i-1}}\right), i = 1, \ldots, 6$ where "P_{t-i}" is the closing price at day t−i	Own calculation based on S&P Global indices
x7	Current Day Return (t)	$r_t = \ln\left(P_t/P_{t-1}\right)$ Where "P_t" is the closing price ad day t	Own calculation based on S&P Global indices
x8 (MA5)	5-day Moving Average of Returns	Arithmetic mean of last 5 daily returns, up to and including day t	Own calculation based on S&P Global indices
x9 (Vol)	5-day Return Volatility	Standard deviation of last 5 daily returns, up to and including day t	Own calculation based on S&P Global indices
Output	Next Day Return (t+1)	$r_{t+1} = \ln\left(P_{t+1}/P_t\right)$ Where "P_{t+1}" is the closing price at day t+1	Own calculation based on S&P Global indices

Note(s): Price data for all indices were obtained from S&P Global. Log return is the natural logarithm of the ratio of consecutive daily prices

Source(s): Our own calculations based on S&P Global and Refinitiv Eikon indices

through wavelet-based analysis. In this way, the study provides a more integrated assessment of weak-form efficiency across markets and periods, including crisis episodes.

3.3 Descriptive statistics

The descriptive statistics show that 5-day return volatility differs across the Islamic indices in the sample, while next-day returns remain close to zero in most cases. Volatility is generally low, but the positive skewness values suggest that sharp increases in volatility occur from time to time. Next-day returns, on the other hand, are mostly slightly negatively skewed. Overall, the results point to some cross-market variation in volatility, whereas average returns remain quite limited.

4. Methodology

In this study, we first use the Fourier-ADF test, introduced by Enders and Lee (2012), to analyze the stationarity of the series. The Fourier-ADF test evaluates the null hypothesis of a unit root against the alternative of stationarity while allowing for smooth structural changes through Fourier (sine and cosine) terms. This feature is particularly useful for long financial samples in which breaks may occur gradually rather than abruptly.

The technique was preferred to conventional unit-root tests, such as ADF or KPSS, because it allows for smooth and gradual structural breaks by including trigonometric terms. This kind of flexibility enables the detection of nonlinear and cyclical variations in financial time series that traditional tests might have missed, leading to more reliable assessments of stationarity in markets that are generally characterized by regime shifts and volatility clustering.

4.1 Research design and methodological rationale

The empirical strategy is organized around three related questions that arise in weak-form efficiency assessments, especially under crisis conditions. First, do the return and volatility series exhibit random-walk or stationarity properties once smooth breaks are allowed for (Fourier-ADF)? Second, even if weak-form tests suggest limited predictability, does any forecasting model generate practically meaningful out-of-sample gains relative to standard random-walk-type benchmarks (ANN forecasting stage)? Third, do volatility and return linkages strengthen at particular horizons and periods, such as crisis windows, in a way that is not visible in purely time-domain averages (WTC time–frequency evidence)? This structure allows the methods to be complementary rather than repetitive.

Following the basic unit root testing, three main methodological approaches were applied sequentially in this study:

(1) The Artificial Neural Network (ANN) model for forecasting,

(2) The Fourier Granger causality approach, and

(3) The Wavelet Transform Coherence (WTC) analysis for time–frequency dependence.

This sequencing is intentional: we start with baseline weak-form diagnostics, then evaluate operational predictability out-of-sample, and finally examine whether crisis-period dynamics vary across horizons in the time–frequency domain.

4.2 Artificial neural network (ANN) model

In the next stage of the study, forecasts are generated using ANN-based machine-learning models. At this stage, a multilayer artificial neural network (ANN, MLP) model is used to predict the next day's return based on the daily returns of the financial indices in the panel. All data used in the model consist of daily price change percentages (log returns) and are found to be stationary in levels based on the stationarity analysis (Fourier-ADF). Therefore, we did not apply additional normalization or standardization, because the inputs are already expressed as stationary log returns on a comparable scale, and we aimed to keep the data treatment consistent across indices to preserve comparability of forecasting performance.

The ANN employs a feedforward network architecture in which data are propagated forward across layers. In this model, data are first received in the input layer, then processed through one or more hidden layers, and finally obtained in the output layer. The number of hidden layers and the number of neurons in each hidden layer determine the complexity and learning capacity of the model. A multilayer neural network is modeled as follows (Heidari *et al.*, 2016; Teixeira Zavadzki de Pauli *et al.*, 2020):

In this study, the model architecture consists of:

(1) Input layer: lagged daily returns,

(2) One hidden layer: 20 neurons using ReLU activation,

(3) Output layer: a single neuron with linear activation for regression output,

(4) Loss function: Mean Squared Error (MSE),

(5) Optimizer: Adam optimizer for adaptive learning and efficient convergence,

(6) Epochs: 200, Batch size: 32.

The network weights were updated using the backpropagation algorithm and the Adam (Adaptive Moment Estimation) optimization algorithm. The main purpose of Adam optimization is to provide faster, more balanced learning than classical optimization methods by combining momentum (the average of past gradients) with adaptive learning rates (step sizes that vary by parameter) when updating network weights. The dataset was split into training and test sets in a 75:25 ratio. The split was implemented chronologically to respect the time-series nature of daily returns: the first 75% of observations were used for training and model selection, while the final 25% were reserved as a genuine out-of-sample test set. Within the training portion, a validation set was used to guide hyperparameter tuning and to apply early stopping based on validation loss. Accordingly, cross-validation and all tuning decisions were confined to the training sample, and the test set was used only once for the final performance evaluation reported in the results section. Hyperparameters (such as the number of hidden layers, number of neurons, and learning rate) were selected through guided tuning using validation performance, with candidate settings evaluated systematically to balance fit and generalization.

This evaluation design also helps prevent information leakage by reserving the test set exclusively for final out-of-sample assessment. The ANN model was therefore implemented using a chronological train-test split, and the test sample was kept untouched until the final evaluation stage. To improve robustness, hyperparameter tuning and validation were performed within the training sample using 5-fold cross-validation and early stopping. In addition, dropout regularization (0.2) was used to limit overfitting.

4.3 Panel Fourier Granger causality

At the subsequent stage of the analysis, we employed the panel Fourier Granger causality approach, originally proposed by Enders and Jones (2014) and later enhanced by Nazlioglu *et al*. (2016) and Yilanci and Gorus (2020) through the inclusion of Fourier functions to examine causal relationships among the variables. While Granger causality is not a direct weak-form efficiency test, it provides complementary evidence on the direction and stability of volatility–return dynamics. In our setting, it helps evaluate whether short-horizon volatility (X9) contains incremental information for next-day returns (Output), which is directly relevant for interpreting predictability claims under stress periods.

In this analysis, our aim is to examine the causal effect of X9 on Output. The following equation is used to test for causality from the independent variable to the dependent variable (Equation (1)):

$$y_{i,t} = \mu_i + \sum_{j=1}^{k_i+d_{max_i}} A_{11} y_{i,t-j} + \sum_{j=1}^{k_i+d_{max_i}} A_{12} x_{i,t-j} + A_{13} \sin\left(\frac{2\pi t f_i}{T}\right) + A_{14} \cos\left(\frac{2\pi t f_i}{T}\right) + u_{i,t} \quad (1)$$

This approach has been preferred over the standard Granger causality test because it accounts for cross-sectional heterogeneity and smooth structural breaks over time. Moreover, by including Fourier terms, it captures gradual changes in the causal relationships rather than abrupt breaks, which is particularly valuable in financial markets characterized by regime evolution and global shocks.

4.4 Wavelet transform coherence (WTC) analysis

In the final stage, Wavelet Transform Coherence (WTC) analysis was used to examine volatility-return relationships across time and frequency. Following Torrence and Webster (1999), wavelet coherence was computed as follows (Equation (2)):

$$W_n^2(s) = \frac{\left|M\left(m^{-1} W_n^{xy}(s)\right)\right|^2}{M\left(m^{-1}\left|W_n^x(s)\right|^2\right) \cdot M\left(m^{-1}\left|W_n^y(s)\right|^2\right)} \quad (2)$$

Values close to zero indicate weak coherence, while values close to one indicate strong coherence. This step helps identify when and at which horizons volatility-return linkages become more pronounced.

5. Empirical results

The FF Fourier-ADF unit root test was applied under both constant and trend specifications to examine the stationarity properties of X9 and Output. Since these series are used in the subsequent causality and WTC analyses, establishing their order of integration is an important first step. The results are summarized in Table 2.

Table 2. Summary of FF Fourier-ADF unit root test results

Country	Variable	Freq. (constant)	FFFADF (constant)	Freq. (trend)	FFFADF (trend)
Canada	X9	1.1	−6.4384	1.7	−6.6628
	Output	4.4	−28.5884	0.4	−28.6008
China Hong Kong	X9	0.7	−8.2317	1.2	−8.3185
	Output	4.2	−28.8982	4.1	−28.9091
India	X9	3	−8.7155	3	−8.7175
	Output	5	−12.6642	5	−12.6911
Japan	X9	3	−8.7095	2.9	−8.7342
	Output	4.4	−26.4011	4.4	−26.3986
Kuwait	X9	0.1	−8.3455	0.6	−8.9767
	Output	0.1	−16.6759	3.5	−16.7415
Malaysia	X9	1.1	−8.1166	1.7	−8.4308
	Output	4.6	−12.3601	4.6	−12.4973
Türkiye	X9	1.3	−13.6591	1.3	−13.66
	Output	3.5	−21.7645	3.6	−21.821
United Kingdom	X9	1.9	−8.4479	1.8	−8.7293
	Output	3.1	−13.6273	3.1	−13.626
United States	X9	1.7	−7.9883	1.7	−7.9863
	Output	4.6	−18.3315	2.9	−18.3516

As shown in Table 2, the findings are fully consistent across the two specifications. Both X9 and Output are stationary in levels for all nine countries under the constant and trend models. This indicates that the series are suitable for the subsequent empirical analyses.

Following the unit root tests, a multilayer artificial neural network (ANN/MLP) model was applied to the nine Dow Jones Islamic indices to predict next-day returns based on past returns. Forecast performance was evaluated on the holdout test sample using RMSE, MAE, and out-of-sample (R^2). To assess whether ANN offers any improvement over a standard benchmark, the results were also compared with those of the random walk model, and the differences in forecast accuracy were tested using the Diebold and Mariano (1995) (DM) test. The combined results are reported in Table 3.

Table 3 shows that the ANN model produces lower RMSE and MAE values than the random walk benchmark for all indices. However, the out-of-sample (R^2) values remain close to zero and are negative throughout, which suggests that next-day returns are still difficult to predict in practical terms. The DM statistics are negative and statistically significant for all indices, indicating that ANN reduces forecast loss relative to the random walk model. Even so,

Table 3. Out-of-sample forecasting performance: ANN, random walk, and DM test

Index	ANN RMSE	ANN MAE	ANN R^2	RW RMSE	RW MAE	RW R^2	DM statistic (p-value)*
DJICA	0.015	0.010	0.000	0.022	0.015	−1.115	−4.877 ($p < 0.001$)
DJICHKU	0.012	0.009	−0.001	0.018	0.013	−1.290	−6.022 ($p < 0.001$)
DJIJP	0.013	0.009	−0.002	0.020	0.014	−1.297	−8.586 ($p < 0.001$)
DJIMIND	0.009	0.006	−0.002	0.012	0.009	−0.841	−6.059 ($p < 0.001$)
DJIMKW	0.010	0.006	−0.001	0.014	0.008	−0.804	−3.707 ($p < 0.001$)
DJIMTR	0.014	0.010	−0.013	0.019	0.014	−0.881	−7.885 ($p < 0.001$)
DJIUK	0.012	0.009	0.000	0.018	0.013	−1.183	−6.262 ($p < 0.001$)
DJMY25D	0.007	0.005	−0.043	0.011	0.007	−1.544	−3.498 ($p = 0.001$)
IMUS	0.011	0.007	0.000	0.017	0.011	−1.215	−4.468 ($p < 0.001$)

these gains should be read as limited improvements in forecast accuracy rather than strong evidence of return predictability. Overall, the results remain broadly consistent with weak-form market efficiency.

Analysis of comparative line and scatter plots and of error histograms for actual and predicted returns shows that the model's predictions cluster around the mean of the observed values and exhibit no systematic predictive power. The forecast graphs of the indices evaluated in the study are also provided in the Supplementary Material (access details are provided in the Data Availability statement). As observed in these graphs, the ANN model closely tracks observed movements in normal periods but deviates slightly during crisis episodes, reflecting limited short-term predictability, consistent with the weak-form EMH. This pattern is theoretically plausible because crisis periods are often associated with abrupt information arrivals, changing expectations, and heightened market uncertainty, which can destabilize short-horizon return dynamics and make one-step-ahead forecasts more difficult (e.g. Gormsen and Koijen, 2020; Ang and Bekaert, 2002). Empirical evidence in finance also suggests that machine learning methods can improve predictive accuracy by capturing nonlinear relationships, but such gains should be interpreted carefully in light of market-state dependence and changing risk conditions (Gu *et al*., 2018; Atsalakis and Valavanis, 2009). From a practical perspective, these observed crisis-period deviations imply that ANN-based forecasts may be more useful as complementary tools for incremental error reduction and risk monitoring, rather than as stand-alone timing signals during stress episodes. This interpretation is also consistent with recent evidence that uncertainty and risk indicators materially affect Islamic equity markets and have direct implications for investors and policymakers (Kazak *et al*., 2025a, b). Accordingly, the crisis-period evidence reinforces our conclusion that any predictive gains remain limited and should not be interpreted as strong evidence against weak-form market efficiency.

The graphs comparing the observed returns in the test set with forecasts from the artificial neural network (ANN) and random-walk models across all indices are provided in the Supplementary Material. As shown, the predictions from both models have limited success in capturing actual returns. Forecasting performance deteriorates, particularly when confronted with extreme values and abrupt changes. Accordingly, this finding indicates that the ANN model cannot predict next-day returns from past price movements in the test set, which holds for all indices. In other words, a weak form of market efficiency is valid in Islamic stock markets.

In subsequent tests, the relationships between X9 and the Output variables were analyzed. First, the Fourier Granger causality test is conducted, and results are presented in Table 4.

Table 4. Results of the Fourier Granger causality test

Country	X9↛Output Wald. stat.	Asympt. *p*.value	Bootstrap *p*.value	Results
Canada	35.855	0.000 (***)	0.000 (***)	X9 ↦ Output
China (Hong Kong)	26.877	0.008 (***)	0.000 (***)	X9 ↦ Output
India	25.282	0.014 (**)	0.000 (***)	X9 ↦ Output
Japan	17.825	0.121	0.000 (***)	X9 ↦ Output
Kuwait	24.226	0.019 (**)	0.000 (***)	X9 ↦ Output
Malaysia	25.116	0.014 (**)	0.100	X9 ↦ Output
Türkiye	16.456	0.171	0.200	X9 ↛ Output
United Kingdom	20.815	0.053 (*)	0.100	X9 ↦ Output
United States	45.834	0.000 (***)	0.000 (***)	X9 ↦ Output

Note(s): ↛ denotes Granger non-causality (H0). "*, ** and ***" denote significance at "10%, 5% and 1%" levels, respectively. "↦" denotes unidirectional causality and "↛" denotes no causal link between the variables (x9 to Output)

Table 4 reports the Fourier Granger causality results for the effect of X9 on Output across countries. The Wald statistic and related *p*-values, supported by the bootstrap method, show that X9 has a significant causal effect on Output in many countries. In particular, for Canada, China (Hong Kong), India, Kuwait, the United Kingdom, and the United States, both the asymptotic and bootstrap *p*-values are statistically significant ($p < 0.05$), indicating rejection of the null hypothesis (H0) and a causal relationship from X9 to Output. Although the bootstrap *p*-values for Japan and Malaysia are significant, the asymptotic *p*-values do not reach statistical significance, suggesting that the causal relationship may vary across countries depending on sample size and methodological sensitivity. In Türkiye, because both *p*-values were not statistically significant, no causal relationship from X9 to Output could be detected.

Finally, wavelet transform coherence (WTC) analysis was used to examine the time-frequency co-movement between volatility (X9) and next-day returns (Output). As shown in the Supplementary Material (access details are provided in the Data Availability statement), warmer colors indicate stronger coherence, while arrows summarize the phase relationship between the two series. Overall, the results point to episodic rather than persistent co-movement across the nine Islamic indices. In most cases, coherence appears in localized clusters and becomes more visible at medium horizons, especially during periods of market stress. For Canada and China/Hong Kong, the volatility-return relationship is generally limited and fragmented across time and scale. Japan and India also show time-varying coherence, with more visible clusters at medium horizons during particular subperiods rather than throughout the sample. A similar pattern appears in Kuwait and Malaysia, where coherence remains weak or intermittent and does not indicate a stable relationship. Türkiye, the United Kingdom, and the United States display relatively broader and more pronounced coherence clusters, especially at medium horizons and during stress periods. Even in these cases, however, the relationship is not uniform across the sample. Taken together, the WTC findings suggest that volatility-return linkages in Islamic equity indices are mostly horizon-specific and temporary, rather than consistent with persistent predictability.

Following the index-level WTC figures, we provide a compact cross-region summary to make the global comparison explicit. While the figures document when and at which horizons volatility (X9) and next-day returns (Output) co-move, a single overview table helps assess whether the strength, dominant horizon, and phase tendency of these linkages differ across major crisis windows. Table 5 therefore synthesizes the WTC evidence by reporting, for each index and crisis period, (1) the strength category, (2) the dominant time horizon (short/ medium/long), and (3) the prevailing phase tendency.

Table 5. Cross-region comparison of volatility–return linkages in crisis windows (WTC summary)

Index	GFC 2007_ 2009	Euro debt 2010_2012	China selloff 2015_16	COVID 2020	Ukraine energy 2022_23
DJICA	H–L–AP	H–L–AP	H–S–IP	H–M–Mixed	H–L–AP
DJICHKU	NA–NA–NA	H–L–AP	H–L–AP	H–M–Mixed	H–M–IP
DJIJP	H–L–Mixed	H–M–AP	H–S–Mixed	H–M–Mixed	H–M–IP
DJIMIND	NA–NA–NA	H–L–Mixed	H–M–AP	H–M–AP	H–L–AP
DJIMKW	H–L–Mixed	H–L–AP	H–L–AP	H–M–AP	H–L–AP
DJMY25D	NA–NA–NA	H–S–AP	H–L–Mixed	H–L–AP	H–S–IP
DJIMTR	H–L–AP	H–S–AP	H–S–Mixed	H–M–AP	H–M–Mixed
DJIUK	H–L–AP	H–L–AP	H–L–Mixed	H–L–AP	H–S–IP
IMUS	H–L–AP	H–L–AP	H–L–Mixed	H–L–AP	H–M–AP

Note(s): Each cell reports Strength-Horizon-Phase for the volatility-return relationship within the relevant crisis window. Strength is coded as H (high), M (medium), L (low), and NA (no significant coherence). Horizon refers to the dominant period band: S (2–16 trading days), M (16–64), and L (64–256). Phase indicates IP (in-phase), AP (anti-phase), or Mixed

Table 5 highlights that volatility–return linkages during crises are not uniform across indices or horizons. In the Global Financial Crisis and the Euro Area debt episode, the dominant coherence is typically concentrated in longer horizons (L) for several major markets (e.g. DJICA, DJIUK, IMUS), whereas some indices show no statistically significant coherence within the cone of influence for the same windows (e.g. DJICHKU, DJIMIND, DJMY25D in 2007–2009). During the COVID-19 window, the dominant horizon shifts toward medium and long bands for many indices, and the phase tendency is more frequently mixed, consistent with heightened and time-varying uncertainty. In the 2022–23 window, the summary suggests greater heterogeneity in both dominant horizons and phase tendencies, with some indices exhibiting shorter-horizon dominance (S) and in-phase tendencies (IP), indicating that crisis-specific conditions can alter the time scale at which volatility and returns co-move.

Regional and global crises such as the 2008 global financial crisis, the COVID-19 shock, and the 2022–2023 geopolitical-energy turbulence appear in the WTC results as localized volatility-return co-movements rather than a stable pattern over the full sample. This is consistent with the Islamic-market literature, which shows that efficiency can vary across markets, regimes, and horizons. Al-Khazali *et al*. (2016), Mensi *et al*. (2017), Buğan *et al*. (2021), and Ülev and Selçuk (2022) all point to time-varying or market-specific efficiency patterns, while Bouoiyour *et al*. (2018) and Sakınç and Sakınç (2024) emphasize cross-market differences in weak-form efficiency.

The horizon structure of the WTC findings also helps explain why the literature reports mixed evidence. In our results, coherence tends to cluster at particular horizons and then fade, rather than forming a continuous forecasting signal. This is in line with Mensi *et al*. (2017) and Buğan *et al*. (2021), and also fits more recent work showing that volatility-correlation patterns in Islamic markets change across crisis periods and should be examined with time-varying methods (Chazi *et al*., 2023; Rehman *et al*., 2024; Tabash *et al*., 2023).

Read together with the Fourier-based Granger results, the picture becomes clearer. In some indices, volatility helps predict next-day returns, while in others the effect is not statistically supported. This again matches earlier studies showing that Islamic equity markets do not follow a single efficiency profile (Al-Khazali *et al*., 2016; Bouoiyour *et al*., 2018; Ülev and Selçuk, 2022; Hassan and Ahmad, 2020; Khan *et al*., 2021; Sakınç and Sakınç, 2024). Our findings suggest that, when predictability appears, it is usually limited to specific windows and horizons rather than indicating persistent weak-form inefficiency.

The forecasting results tell a similar story. ANN produces lower forecast errors than the random walk benchmark, but the out-of-sample R^2 values are still close to zero and in some cases negative. So, even if the model performs better in statistical terms, this does not mean that returns become meaningfully predictable in practice. As Showalter and Gropp (2019) also note, a better fit does not automatically translate into an economically useful trading opportunity. Taken together, the findings suggest that weak-form efficiency is still broadly consistent with the data, even though crisis periods may create short-lived dependence that does not persist long enough to generate systematic excess returns (Emenike and Joseph, 2018; Hailu and Vural, 2020).

6. Conclusion and discussion

This study examined weak-form efficiency in nine Dow Jones Islamic stock indices using unit root testing, Fourier-based Granger causality, ANN forecasting, and wavelet transform coherence analysis. The aim was to assess whether return predictability is persistent and whether volatility-return linkages become more visible during crisis periods.

The findings point to a clear overall pattern. Weak-form efficiency remains broadly consistent with the data. Although ANN produces lower forecast errors than the random walk benchmark, the out-of-sample explanatory power remains very limited. The WTC results show that volatility-return linkages become more visible during major stress episodes, but these effects are localized and short-lived rather than stable over time.

The study contributes to the literature by examining a broad set of Islamic indices within a single framework and by showing that efficiency in these markets is better understood as time-varying and crisis-sensitive. This helps explain why earlier studies report mixed findings across markets and periods.

The results also carry practical implications. During crisis periods, Islamic equity markets may deserve closer attention, since temporary dependence becomes easier to observe in such episodes. For investors and fund managers, the main message is one of caution. Short-lived co-movements may become more noticeable under stress, but they do not seem stable enough to offer a reliable basis for persistent excess returns.

Overall, the evidence suggests that Islamic equity markets remain broadly compatible with weak-form efficiency, even though crisis periods may create temporary and horizon-specific departures.

Data availability statement
The supplementary figures and data supporting the findings of this study are openly available in the Harvard Dataverse repository at https://doi.org/10.7910/DVN/8BRAQZ

Supplementary material
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References

Adegboyo, O.S. and Sarwar, K. (2025), "Modelling and forecasting of Nigeria stock market volatility", *Future Business Journal*, Vol. 11 No. 1, p. 124, doi: 10.1186/s43093-025-00536-4.

Aharon, D.Y., Ali, S. and Naveed, M. (2025), "Who A(m) I? Exploring quantile frequency connectedness in emerging AI and IoT token markets", *The North American Journal of Economics and Finance*, Vol. 80, 102497, doi: 10.1016/j.najef.2025.102497.

Ahmad, W. and Erdem, İ. (1996), "Weak form efficiency in the thinly traded Pakistani stock market", *METU Studies in Development*, Vol. 23 No. 3, pp. 313-327.

Al-Khazali, O.M., Leduc, G. and Alsayed, M.S. (2016), "A market efficiency comparison of Islamic and non-Islamic stock indices", *Emerging Markets Finance and Trade*, Vol. 52 No. 7, pp. 1587-1605, doi: 10.1080/1540496X.2014.998572.

Al-wazier, R.A.-S. (2024), "Testing weak form efficiency of the Egyptian and Saudi stock markets", *Scientific Journal for Financial and Commercial Studies and Research*, Vol. 5 No. 1, pp. 893-915, doi: 10.21608/cfdj.2024.328568.

Ali, S., Shahzad, S.J.H., Raza, N. and Al-Yahyaee, K.H. (2018), "Stock market efficiency: a comparative analysis of Islamic and conventional stock markets", *Physica A: Statistical Mechanics and its Applications*, Vol. 503, pp. 139-153, doi: 10.1016/j.physa.2018.02.169.

Ali, S., Naveed, M., Saleem, A. and Nasir, M.W. (2022), "Time-frequency co-movement between Covid-19 and Pakistan's stock market: empirical evidence from wavelet coherence analysis", *Annals of Financial Economics*, Vol. 17 No. 04, 2250026, doi: 10.1142/S2010495222500269.

Ali, S., Al-Nassar, N.S. and Naveed, M. (2024a), "Bridging the gap: uncovering static and dynamic relationships between digital assets and BRICS equity markets", *Global Finance Journal*, Vol. 60, 100955, doi: 10.1016/j.gfj.2024.100955.

Ali, S., Umar, M., Naveed, M. and Shan, S. (2024b), "Assessing the impact of renewable energy tokens on BRICS stock markets: a new diversification approach", *Energy Economics*, Vol. 134, 107523, doi: 10.1016/j.eneco.2024.107523.

Ang, A. and Bekaert, G. (2002), "International asset allocation with regime shifts", *The Review of Financial Studies*, Vol. 15 No. 4, pp. 1137-1187, doi: 10.1093/rfs/15.4.1137.

Atsalakis, G.S. and Valavanis, K.P. (2009), "Surveying stock market forecasting techniques – Part II: soft computing methods", *Expert Systems with Applications*, Vol. 36 No. 3, Part 2, pp. 5932-5941, doi: 10.1016/j.eswa.2008.07.006.

Awan, U. and Subayyal, M. (2016), "Weak form efficient market hypothesis study: evidence from Gulf stock markets", *SSRN Electronic Journal*, pp. 218-231, doi: 10.2139/ssrn.2787816.

Bagwan, A.S., Pachpatte, D.B., Kiseľák, J. and Stehlík, M. (2025), "On existence results of boundary value problems of Caputo fractional difference equations for weak-form efficient market hypothesis", *Stochastic Analysis and Applications*, Vol. 43 No. 1, pp. 30-47, doi: 10.1080/07362994.2024.2424343.

Benthabet, S. and Benthabet, A. (2023), "Testing of weak form efficient market hypothesis: evidence from the hat bourse (2010-2019): Tester la forme faible de l'hypothese d'efficience du marche financiers: Preuve de la bourse de Casablanca (2010-2019)", *les cahiers du cread*, Vol. 39 No. 1, pp. 225-247, doi: 10.4314/cread.v39i1.8.

Bouoiyour, J., Selmi, R. and Wohar, M.E. (2018), "Are Islamic stock markets efficient? A multifractal detrended fluctuation analysis", *Finance Research Letters*, Vol. 26, pp. 100-105, doi: 10.1016/j.frl.2017.12.008.

Buğan, M.F., ÇevİK, E.İ., Kirci ÇevİK, N. and Yildirim, D.Ç. (2021), "Testing adaptive market hypothesis in global Islamic stock markets: evidence from Markov-switching ADF test", *Bilimname*, Vol. 2021 No. 44, pp. 425-449, doi: 10.28949/bilimname.866724.

Çevik, E.İ. (2018), "Borsa İstanbul Zayıf Formda Etkin mi? Markov-switching ADF Testi Yaklaşımı", *BDDK Bankacılık ve Finansal Piyasalar*, Vol. 12 No. 2, pp. 9-30.

Chazi, A., Samet, A. and Azad, A.S.M.S. (2023), "Volatility and correlation of Islamic and conventional indices during crises", *Global Finance Journal*, Vol. 55, 100800, doi: 10.1016/j.gfj.2022.100800.

Diallo, O.K., Mendy, P. and Burlea-Schiopoiu, A. (2021), "A method to test weak-form market efficiency from sectoral indices of the WAEMU stock exchange: a wavelet analysis", *Heliyon*, Vol. 7 No. 1, e05858, doi: 10.1016/j.heliyon.2020.e05858.

Dias, R., Heliodoro, P., Teixeira, N. and Godinho, T. (2020), "Testing the weak form of efficient market hypothesis: empirical evidence from equity markets", *International Journal of Accounting, Finance and Risk Management*, Vol. 5 No. 1, p. 40, doi: 10.11648/j.ijafrm.20200501.14.

Diebold, F. and Mariano, R. (1995), "Predictive accuracy", *Journal of Business and Economic Statistics*, Vol. 13 No. 3, pp. 253-263, doi: 10.1080/07350015.1995.10524599.

Dubey, T. (2023), "Study of weak form of market efficiency in India", *International Journal of Advanced Research*, Vol. 11 No. 07, pp. 1171-1178, doi: 10.21474/IJAR01/17331.

El-Diftar, D. (2024), "The applicability of the efficient market hypothesis in emerging markets", *The Arab Journal of Administration*, Vol. 44 No. 4, 4, doi: 10.21608/aja.2021.89040.1130.

Emenike, K.O. and Joseph, K.K.B. (2018), "Empirical evaluation of weak-form efficient market hypothesis in Ugandan securities exchange", (SSRN Scholarly Paper 3596180), Social Science Research Network, available at: https://papers.ssrn.com/abstract=3596180

Enders, W. and Jones, P. (2014), "Grain prices, oil prices, and multiple smooth breaks in a VAR", *Studies in Nonlinear Dynamics and Econometrics*, Vol. 20 No. 4, pp. 399-419, doi: 10.1515/snde-2014-0101.

Enders, W. and Lee, J. (2012), "The flexible Fourier form and Dickey–Fuller type unit root tests", *Economics Letters*, Vol. 117 No. 1, pp. 196-199, doi: 10.1016/j.econlet.2012.04.081.

Fama, E.F. (1965), "The behavior of stock-market prices", *The Journal of Business*, Vol. 38 No. 1, pp. 34-105, doi: 10.1086/294743, available at: http://www.jstor.org/stable/2350752

Fama, E.F. (1970), "Efficient capital markets: a review of theory and empirical work", *The Journal of Finance*, Vol. 25 No. 2, pp. 383-417, doi: 10.2307/2325486.

Fattahi, S. (2010), "Weak- form efficiency in the German stock market", *Iranian Economic Review*, Vol. 15 No. 27, pp. 77-94.

Frimpong, J.M. and Oteng-Abayie, E.F. (2007), "Market returns and weak-form efficiency: the case of the Ghana stock exchange", [MPRA Paper], available at: https://mpra.ub.uni-muenchen.de/7582/

Gazel, S. (2020), "The weak form market efficiency in the MSCI ETF indices: conventional and the Fourier unit root test on the developed and developing countries", *Business and Management Studies: An International Journal*, Vol. 8 No. 4, pp. 409-423, doi: 10.15295/bmij.v8i4.1722.

Gimba, V.K. (2012), "Testing the weak-form efficiency market hypothesis: evidence from Nigerian stock market", *CBN Journal of Applied Statistics*, Vol. 3 No. 1, pp. 117-136.

Gormsen, N.J. and Koijen, R.S.J. (2020), "Coronavirus: impact on stock prices and growth expectations", *The Review of Asset Pricing Studies*, Vol. 10 No. 4, pp. 574-597, doi: 10.1093/rapstu/raaa013.

Gu, S., Kelly, B. and Xiu, D. (2018), "Empirical asset pricing via machine learning", (Working Paper No. 25398), National Bureau of Economic Research, doi: 10.3386/w25398.

Hailu, S.M. and Vural, G. (2020), "Testing the weak form market efficiency of Borsa Istanbul: an empirical evidence from Turkish banking sector stocks", *Pressacademia*, Vol. 7 No. 3, pp. 236-249, doi: 10.17261/Pressacademia.2020.1291.

Hassan, N. and Ahmad, H.Z. (2020), "Testing the weak form state of market efficiency: an empirical evidence of Sharı'ah compliant index", *Journal of Islamic Business and Management (JIBM)*, Vol. 10 No. 02, pp. 418-435, doi: 10.26501/jibm/2020.1002-008.

Heidari, E., Sobati, M.A. and Movahedirad, S. (2016), "Accurate prediction of nanofluid viscosity using a multilayer perceptron artificial neural network (MLP-ANN)", *Chemometrics and Intelligent Laboratory Systems*, Vol. 155, pp. 73-85, doi: 10.1016/j.chemolab.2016.03.031.

Hepsağ, A. and Akçalı, B.Y. (2015), "Zayıf Formda Piyasa Etkinliğinin Asimetrik Doğrusal Olmayan Birim Kök Testi ile Analizi: G-7 ve E-7 Ülkeleri Örneği", *BDDK Bankacılık ve Finansal Piyasalar Dergisi*, Vol. 9 No. 2, 2.

Ikeora, J.J.E., Charles-Anyaogu, N.B. and Andabai, P.W. (2016), "The weak form efficient market hypothesis in the Nigerian stock market: an empirical investigation", *European Journal of Business, Economics and Accountancy*, Vol. 4 No. 6, pp. 93-105.

Islamic Financial Services Board (IFSB) (2025), Islamic Financial Services Industry (Stability Report) 2025, Islamic Financial Services Board (IFSB), available at: https://www.ifsb.org/wp-content/uploads/2025/05/IFSI-Stability-Report-2025.pdf

Joshi, M. (2024), "Broad market indices of Nepal stock exchange: testing of efficient market hypothesis", *Apex Journal of Business and Management*, Vol. 3 No. 2, pp. 25-36, doi: 10.61274/apxc.2024.v03i02.003.

Karademi̇r, F. and Evci̇, S. (2020), "Borsa İstanbul'da Zayıf Formda Piyasa Etkinliğinin Test Edilmesi: Sektörel Çerçevede Bir Analiz", *Business and Management Studies: An International Journal*, Vol. 8 No. 1, pp. 1-100, doi: 10.15295/bmij.v8i1.1416.

Katabi, M.M. and Raphael, G. (2018), "An empirical analysis of weak-form efficiency of Dar es Salaam Stock Exchange", *African Journal of Economic Review*, Vol. 6 No. 2, pp. 115-134.

Kazak, H., Kumar, S., Gündüz, M.A., Akcan, A.T. and Bilgiç, H.H. (2025a), "Metaheuristic-optimized ANFIS and ANN models for stock price forecasting: evidence from the Borsa Istanbul 100 index", *Discover Artificial Intelligence*, Vol. 5 No. 1, p. 272, doi: 10.1007/s44163-025-00395-6.

Kazak, H., Saiti, B., Kılıç, C., Akcan, A.T. and Karataş, A.R. (2025b), "Impact of global risk factors on the Islamic stock market: new evidence from wavelet analysis", *Computational Economics*, Vol. 65 No. 6, pp. 3573-3604, doi: 10.1007/s10614-024-10665-7.

Khan, N.U. and Khan, S. (2016), "Weak form of efficient market hypothesis – evidence from Pakistan", *Business and Economic Review*, Vol. 8 No. Special Edition, pp. 1-18, doi: 10.22547/BER/8.SE.1.

Khan, A.Q., Ikram, S. and Mehtab, M. (2011), "Testing weak form market efficiency of Indian capital market: a case of national stock exchange (NSE) and Bombay stock exchange (BSE)", *African Journal of Marketing Management*, Vol. 3 No. 6, pp. 115-127.

Khan, A., Khan, M.Y., Khan, A.Q., Khan, M.J. and Rahman, Z.U. (2021), "Testing the weak form of efficient market hypothesis for socially responsible and Shariah indexes in the USA", *Journal of Islamic Accounting and Business Research*, Vol. 12 No. 5, pp. 625-645, doi: 10.1108/JIABR-02-2020-0055.

Kok, S.C. and Munir, Q. (2015), "Malaysian finance sector weak-form efficiency: heterogeneity, structural breaks, and cross-sectional dependence", *Journal of Economics, Finance and Administrative Science*, Vol. 20 No. 39, pp. 105-117, doi: 10.1016/j.jefas.2015.10.002.

Kumar, H. and Jawa, R. (2017), "Efficient market hypothesis and calendar effects: empirical evidences from the Indian stock markets", (SSRN Scholarly Paper 2981633), Social Science Research Network, available at: https://papers.ssrn.com/abstract=2981633

Lee, M.-J. and Choi, S.-Y. (2023), "Comparing market efficiency in developed, emerging, and Frontier equity markets: a multifractal detrended fluctuation analysis", *Fractal and Fractional*, Vol. 7 No. 478, 6, doi: 10.3390/fractalfract7060478.

Luo, J., Zhang, M. and Zhang, Y. (2022), "An empirical study on the efficiency of the Chinese stock market", *2022 International Conference on Mathematical Statistics and Economic Analysis (MSEA 2022)*, Atlantis Press, pp. 690-698.

Malini, H. (2019), "Efficient market hypothesis and market anomalies of LQ 45 index in Indonesia stock exchange", *Sriwijaya International Journal of Dynamic Economics and Business*, Vol. 3 No. 2, pp. 107-121, doi: 10.29259/sijdeb.v3i2.107-121.

Marsani, M.F., Shabri, A., Basri, B., Mat Jan, N.A. and Mohd Kasihmuddin, M.S. (2022), "Efficient market hypothesis for Malaysian extreme stock return: peaks over a threshold method", *Matematika*, Vol. 38 No. 2, pp. 141-155, doi: 10.11113/matematika.v38.n2.1396.

Mensi, W., Tiwari, A.K. and Yoon, S.-M. (2017), "Global financial crisis and weak-form efficiency of Islamic sectoral stock markets: an MF-DFA analysis", *Physica A: Statistical Mechanics and its Applications*, Vol. 471, pp. 135-146, doi: 10.1016/j.physa.2016.12.034.

Naveed, M. and Ali, S. (2024), "Does risk tolerance mediates the relationship between financial literacy and financial wellbeing during COVID-19: empirical evidence from an emerging economy", *Sage Open*, Vol. 14 No. 4, doi: 10.1177/21582440241297065.

Naveed, M., Ali, S., Iqbal, K. and Sohail, M.K. (2020), "Role of financial and non-financial information in determining individual investor investment decision: a signaling perspective", *South Asian Journal of Business Studies*, Vol. 9 No. 2, pp. 261-278, doi: 10.1108/SAJBS-09-2019-0168.

Naveed, M., Ali, S. and Tiwari, A.K. (2025), "Tracing the ties that bind: navigating the static and dynamic connectedness between NFTs and equity markets in ASEAN based on QVAR-approach", *Financial Innovation*, Vol. 11 No. 1, p. 33, doi: 10.1186/s40854-024-00718-z.

Nazlioglu, S., Gormus, N.A. and Soytas, U. (2016), "Oil prices and real estate investment trusts (REITs): gradual-shift causality and volatility transmission analysis", *Energy Economics*, Vol. 60, pp. 168-175, doi: 10.1016/j.eneco.2016.09.009.

Nik, S. and Marko, J. (2023), "Testing market efficiency in emerging markets' stock indices with runs tests", *Socratic Lectures*, Vol. 8, pp. 125-129, doi: 10.55295/PSL.2023.II17.

Ogbulu, O.M. (2016), "Weak-form market efficiency, estimation interval and the Nigerian stock exchange: empirical evidence", *International Academy of Business Review*, Vol. 3 No. 1, pp. 42-61.

Özmerdi̇vanli, A. (2024), "Hisse Senedi ve Döviz Piyasalarında Zayıf Formda Etkinliğin test Edilmesi: Türkiye Örneği", *Uluslararasi Akademik Birikim Dergisi*, Vol. 7 No. 5, 5.

Pervez, M., Rashid, M.H.U., Chowdhury, M.A.I. and Rahaman, M. (2018), "Predicting the stock market efficiency in weak form: a study on Dhaka stock exchange", *International Journal of Economics and Financial Issues*, Vol. 8 No. 5, 5.

Raquib, M. and Alom, K. (2015), "Are the emerging capital markets weak form efficient? - evidence from the model of the Dhaka stock exchange", *Universal Journal of Accounting and Finance*, Vol. 3 No. 1, pp. 1-8, doi: 10.13189/ujaf.2015.030101.

Rehman, M.U., Saleem, A. and Sági, J. (2024), "Oil crisis vs pandemic: a broader outlook of time-frequency volatility transmission between Islamic and conventional stock markets", *Cogent Economics and Finance*, Vol. 12 No. 1, 2365366, doi: 10.1080/23322039.2024.2365366.

Risal, H.G. and Koju, P. (2021), "Testing the weak form of efficiency in Nepalese stock markets", *SEBON Journal*, Vol. VIII No. 1, pp. 20-33.

Saeedi, A., Miraskari, S.R. and Ara, M.S. (2014), "The investigation of the efficient market hypothesis: evidence from an emerging market", *Taylor's Business Review (TBR)*, Vol. 4 No. 2, p. 1, doi: 10.7603/s40932-014-0001-0.

Sakınç, S.Ö. and Sakınç, İ. (2024), "Borsa İstanbul Katılım Endekslerinin Etkin Piyasa Hipotezi Analizi: Zayıf Formda Etkinlik İncelemesi", *Hitit Sosyal Bilimler Dergisi*, Vol. 17 No. ICAFR'23 Özel Sayısı, pp. 42-53, doi: 10.17218/hititsbd.1391325.

Samuelson, P.A. (1965), "Proof that properly anticipated prices fluctuate randomly", *Industrial Management Review*, Vol. 6 No. 2, pp. 41-49.

Showalter, S. and Gropp, J. (2019), "Validating weak-form market efficiency in United States stock markets with trend deterministic price data and machine learning", arxiv: 1909.05151, doi: 10.48550/arXiv.1909.05151.

Tabash, M.I., Sahabuddin, M., Abdulkarim, F.M., Hamouri, B. and Tran, D.K. (2023), "Dynamic dependency between the Shariah and traditional stock markets: diversification opportunities during the COVID-19 and global financial crisis (GFC) periods", *Economies*, Vol. 11 No. 5, p. 149, doi: 10.3390/economies11050149.

Teixeira Zavadzki de Pauli, S., Kleina, M. and Bonat, W.H. (2020), "Comparing artificial neural network architectures for Brazilian stock market prediction", *Annals of Data Science*, Vol. 7 No. 4, pp. 613-628, doi: 10.1007/s40745-020-00305-w.

Torrence, C. and Webster, P.J. (1999), "Interdecadal changes in the ENSO–monsoon system", *Journal of Climate*, Vol. 12 No. 8, pp. 2679-2690, doi: 10.1175/1520-0442(1999)012<2679:ICITEM>2.0.CO;2.

Trang, N.N.M. (2022), *Market Efficiency Hypothesis in Emerging Stock Markets*, Aalto University School of Business Bachelor's Program in International Business.

Tutar, N.K. and Dalgar, H. (2023), "Etkin Piyasa Hipotezinin İncelenmesi: G-20 Ülkelerinden Kanıtlar", *Journal of Social, Humanities and Administrative Sciences (JOSHAS)*, Vol. 9 No. 62, pp. 2542-2551, doi: 10.29228/JOSHAS.68636.

Ülev, S. and Selçuk, M. (2022), "Testing the weak-form market efficiency for the Islamic market indices: evidence from Fourier wavelet ADF unit root test", *Journal of Economic Policy Researches/İktisat Politikası Araştırmaları Dergisi*, Vol. 9 No. 2, pp. 315-329, doi: 10.26650/JEPR1111585.

Yavrumyan, E. (2015), "Efficient market hypothesis and calendar effects: evidence from the Oslo stock exchange", [Master thesis], available at: https://www.duo.uio.no/handle/10852/44341

Yilanci, V. and Gorus, M.S. (2020), "Does economic globalization have predictive power for ecological footprint in MENA counties? A panel causality test with a Fourier function", *Environmental Science and Pollution Research*, Vol. 27 No. 32, pp. 40552-40562, doi: 10.1007/s11356-020-10092-9.

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