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Time-Varying Market Efficiency in the Turkish Stock Market: Evidence from an Entropy-Based Analysis

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Abstract

This study analyzes the time-varying informational efficiency of the Borsa Istanbul composite index (XU100) and its main sector indices from January 2017 to June 2023. The sample entropy method is used to measure market efficiency across multiple timescales ranging from 1 to 30 business days, and a rolling window approach is used to capture daily informational efficiency dynamics. Our findings indicate that market efficiency decreases as the timescale increases, which suggests that indices are more efficient in the short-term periods than in the long-term periods. Among the indices, BIST Financials (XUMAL) has the highest average efficiency, while BIST Technology (XUTEK) displays the lowest. The results also reveal that efficiency levels across all indices fluctuate widely on a daily basis, and a particularly sharp decline was noticed during the onset of the COVID-19 pandemic. This suggests that a major disruption in informational efficiency occurred during this time. The Russia-Ukraine war and the 2023 February earthquake further weakened the efficiency of all indices, though their impacts were comparatively less severe than COVID-19. An entropic correlation analysis reveals strong positive correlations between XU100 and BIST Industrials, which highlights that these indices are related in terms of efficiency dynamics. This study offers new insights into the dynamic nature of market efficiency in the Turkish stock market, emphasizing that informational efficiency is strongly influenced by sector-specific characteristics and external shocks. Our empirical findings strongly support the Adaptive Market Hypothesis (AMH), confirming that market efficiency evolves dynamically in response to changing market conditions and external events.

Keywords: Informational Efficiency, Adaptive Market Hypothesis, Sample Entropy, Borsa Istanbul, Extreme events.

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1. INTRODUCTION

The efficient market hypothesis (EMH) is one of the fundamental theories of finance and has long been the subject of debate in various studies. The weak form of the EMH contends that it is unfeasible to create an investing strategy that continuously outperforms the market because all previous market prices have already been included in asset values. The underlying assumption of weak form efficiency is that price movements are random, rendering them unpredictable and unexploitable (Fama, 1970).

The traditional EMH framework assumes that markets maintain efficiency under all conditions, but this assumption has been widely contested. The evidence in the literature suggests that panic and investors' irrational behaviour following wars, crises, shocks and bubbles lead to asset prices diverging from their fundamental values, violating the efficient markets hypothesis (Ali et al., 2020; Gaio et al., 2022; Kim et al., 2011; Lalwani & Meshram, 2020; Lim et al., 2008; Lim et al., 2013; Özkan, 2021; Vasileiou, 2021).

The Adaptive Market Hypothesis (AMH), introduced by Lo (2004), suggests that market efficiency evolves as economic and geopolitical conditions change over time. According to this approach, financial markets alternate between periods of efficiency and inefficiency depending on investor behavior, economic policies, and crisis events. In previous studies, it has been demonstrated that market efficiency is highly sensitive to financial and economic crises, highlighting the need for a more dynamic approach to measuring it (Alvarez-Ramirez et al., 2012; Ortiz-Cruz et al., 2012; Patra & Hiremath, 2022).

Financial markets have experienced several shocks in recent years, including the COVID-19 pandemic and the Russian-Ukraine conflict, which are critical to test the robustness and adaptability of market efficiency. A growing body of international literature examines market efficiency during the COVID-19 (Ammy-Driss & Garcin, 2023; Choi, 2021; Gaio et al., 2022; Özkan, 2021). These studies generally concluded that financial markets were not efficient during these time periods. A number of studies have also examined how these crises impacted Turkish financial markets. Özkan (2022) investigated the effects of the Russia-Ukraine war on market efficiency in Türkiye and found significant declines following the war. Erer et al. (2023) presented the distinct dynamics of sectoral market efficiency in Türkiye during COVID-19 and the global financial crisis. Yıldıran (2021) also evaluated financial market efficiency in Türkiye during COVID-19 and found there was a significant decline in efficiency. Suyadal (2021) examined the EMH for the countries with the greatest impact from COVID-19 (U.S.A., France, Brazil, India, Türkiye, and Russia). The author used the Run Test and the findings revealed that while USA and Brazil’s markets are inefficient during COVID-19, other markets were found to be efficient. Unal (2020) investigated the financial impacts of the pandemic on several industries in Borsa Istanbul. In the study, the overreaction hypothesis was tested and it was determined

that leather clothing, transportation logistics, marketing, tourism and airlines are the sectors that are most severely impacted by COVID-19.

In addition to global crises, the Turkish economy has faced a number of challenges that have likely affected the efficiency of the market. During the Turkish currency crisis of 2018, the Turkish lira plunged sharply, which caused the liquidity issues and a spike in financial market volatility. More recently, ongoing inflation has caused extreme fluctuations in asset prices due to monetary policies and rising inflation rates. Moreover, after the 2023 February earthquake, Borsa Istanbul was closed for five days, followed by a sharp market reaction after reopening.

Given the complexity of the problem, it is important to determine whether Borsa Istanbul is efficient or not, as well as to provide quantitative indicators of informational efficiency and to assess temporal changes associated with socioeconomic factors. To achieve this, we utilize the sample entropy method to estimate the daily evolving informational efficiency.

Entropy, which has been used in many studies to analyze the market efficiency (Alvarez-Ramirez et al., 2012; Oh et al., 2007; Ortiz-Cruz et al., 2012; Wang & Wang, 2021; Wang et al., 2012), calculates the level of informational efficiency over time and provides more information. Traditional market efficiency tests, such as the Variance Ratio Test, Runs Test, and Augmented Dickey-Fuller (ADF) Test, classify financial markets in a strict efficient or inefficient framework, which assumes a binary structure. However, these methods fail to account for the nonlinear dependencies. Financial markets are neither perfectly efficient nor entirely inefficient but operate on a continuum of efficiency levels that evolve over time. Unlike traditional tests, which offer only categorical classifications, entropy-based methods provide a more nuanced and dynamic measure of efficiency, which provide a continuous measure of efficiency and allow us to assess partial efficiency states rather than imposing strict classifications.

To overcome these limitations of traditional methods, we employ Sample Entropy (SampEn) and Multiscale Sample Entropy (MSE) in this study, which quantify the degree of randomness and complexity in stock returns. SampEn, in particular, is a more sensitive tool for detecting informational efficiency variations, as it captures irregularities in price movements that traditional statistical tests might overlook. By evaluating market efficiency across different time horizons, MSE further enhances this analysis, making it possible to track short-term and long-term efficiency trends dynamically. The methodological details of these entropy-based techniques and their advantages over conventional approaches are discussed in Section 3.

This research focuses primarily on the application of entropy-based methods to analyze dynamic changes in Turkish market efficiency over extended periods, which includes recent global crises (COVID-19, Russian-Ukraine conflict) and domestic crises (currency crisis, inflation crisis, and a major earthquake in 2023). In this context, this study aims to answer the following critical research questions:

1. How has the Turkish stock market's informational efficiency evolved from 2017 to 2023, particularly in light of recent global and domestic crises?

2. Do specific sectors within Borsa Istanbul demonstrate different informational efficiency profiles during this period? How do these external shocks shape market dynamics at the sectoral level?

3. Is there a relationship between different sectoral indices in terms of informational complexity?

4. How do market efficiency dynamics vary over short-term and long-term horizons when examined across multiple timescales (1 to 30 business days)?

5. Are the observed patterns of informational efficiency consistent with the Adaptive Market Hypothesis (AMH)?

By addressing these questions, this article offers insights into Borsa Istanbul's resilience and adaptability under crises by conducting an entropy-based analysis of time-varying efficiency.

This study makes several distinct contributions to the existing literature by considering both global and domestic crises in a long-run efficiency analysis by integrating an entropy-based framework. By capturing the dynamic evolution of market efficiency, it allows us to better understand how different sectors in Borsa Istanbul react to economic shocks. The proposed approach fills an important gap in the literature on the Turkish stock market's efficiency. This comprehensive analysis enables how patterns of efficiency vary across industries and over time.

The paper is organized as follows: Section 2 covers the literature review. Section 3 outlines the methodology. Section 4 provides data and parameter selection. Empirical results are reported in Section 5. Finally, Section 6 concludes with key findings and implications.

2. LITERATURE REVIEW

Market efficiency is widely discussed as the focus of financial studies (Aggarwal, 2019; Darrat & Zhong, 2000; Durusu-Ciftci et al., 2019; Huang, 2019; Palamalai et al., 2021; Poshakwale, 2002; Rehman et al., 2018; Rizvi & Arshad, 2014; Sadat & Hasan, 2019; Shternshis et al., 2022; Stakić et al., 2016; Tiwari & Kyophilavong, 2014).

In studies involving crisis and shock periods, Lim et al. (2008) studied the effects of the 1997 financial crisis on the efficiency of eight Asian stock markets, using the rolling bicorrelation test statistics. According to their findings, during the crisis, most Asian stock markets experienced adverse effects on their efficiency, but after the crisis, many of these markets returned to their pre-crisis efficiency levels. During the financial crisis period, Mishra et al. (2009) examined the efficiency of the Indian stock market and found that the stock market was weak-form inefficient. According to Chen & Jarrett (2011), the Chinese stock markets were not efficient prior to the financial crisis and turned out to be weakly efficient during the crisis. Anagnostidis et al. (2016) investigated the impact of the global

finance crisis on Eurozone stock market efficiency, applying Dynamic Hurst exponents and rolling window technique. The findings indicated that stock price efficiency was negatively impacted by the 2008 crisis in the majority of Eurozone markets.

Choi (2021) conducted a study covering both the global crisis and the COVID-19 pandemic and identified sectors with low market efficiency for the two crisis periods by using the S&P 500 index data. The findings revealed that the efficiency of the real estate sector and the IT sector were low in the global crisis, while the efficiency of the material sector was low due to the stagnation in the manufacturing industry during the COVID-19 pandemic. Ahmed (2021) focused on market efficiency of Dhaka Stock Exchange in COVID-19. The results rejected the random walk and concluded that the market was inefficient. Wang and Wang (2021) applied the multiscale entropy method by using daily data of S&P 500 index, Bitcoin and US dollar index and gold futures prices during the COVID-19 period. From the outcomes of this research, it was determined that the market efficiency decreased significantly in all markets in the period of February 2020 – March 2020.

In other entropy-based studies, Alvarez-Ramirez et al. (2012) determined that the level of market efficiency of the Dow Jones Index varies over time and is time scale dependent. Shternshis et al. (2022) used the data of the 100 most liquid stocks in the Russell 3000 index for the period 02.01.1998 - 23.06.2017, and the data of the Exchange Traded Funds (ETF) from 02.01.2003 to 01.12.2009. In the study, it was concluded that the market was not efficient on a one-minute time scale and weekly.

A number of studies have shown that the conflict between Russia and Ukraine impacts the efficiency of the market as well. According to Özkan (2022), the conflict caused the Turkish stock market to become less efficient, more volatile, and generated abnormal returns. Gaio et al. (2022) also found that conflict affected developed stock markets by increasing multifractality and reducing market efficiency. Memon et al. (2024) studied the efficiency and herding behavior of G20 stock markets during the Russia-Ukraine War and COVID-19 pandemic. Developed stock markets were more efficient than emerging markets. Italy was the least efficient and Germany the most efficient. The study also found that the impact of crises on market efficiency varies from one market to another, with developed markets showing a greater degree of resilience. Maurya et al. (2024) examined the dynamic link between market volatilities during the COVID-19 pandemic and the Russia-Ukraine conflict. The study found that volatility connectedness increased significantly during these periods. Developed countries were net volatility transmitters, while developing countries were net volatility receivers. This suggests that global crises significantly affect market volatility and efficiency.

There are many studies in the literature investigating the efficiency of Borsa Istanbul. Some of these studies report that there is insufficient evidence to support the EMH (Bal et al., 2021; Bektur & Aydın, 2019; Duman Atan et al., 2009; Gözbaşı, 2014; Karademir & Evci, 2020; Yücel, 2016; Zeren et al., 2013). Others conclude that stock prices behave according to the theory (Altunöz, 2020; Ayaydın et

al., 2018; Aytekin et al., 2021; Çevik, 2012; Çevik & Erdoğan, 2009; Malcıoğlu & Aydın, 2016; Şahin, 2020; Tanrıöver & Çöllü, 2015).

In recent years, research has expanded to test the weak-form efficiency of Islamic indices in Borsa Istanbul. Özkan and Çakar (2020) examined weak-form efficiency of Turkish Islamic indices by using autocorrelation analyses. They found that while these indices generally exhibit weak-form efficiency, there are occasional deviations on certain dates that allow abnormal returns. Similarly, Sakınç and Sakınç (2023) found that Borsa Istanbul (BIST) Participation Indices do not meet the weak-form efficiency criteria.

Sectoral differences in weak-form efficiency have also been a focus of research. Özkan (2020a) used the automatic portmanteau test on 19 primary sector indices of Borsa Istanbul to compare market efficiency. According to the study, sectors such as transportation, insurance, electricity, and metal products machinery exhibit higher return predictability and lower market efficiency than other sectors, while sectors like food and beverage, banking, wholesale and retail trade, and wood-paper-printing sectors are found to be more efficient. Dallı and Uğur (2022) tested the weak form efficiency of the BIST Food and Beverage Index using unit root and variance ratio tests on monthly closing prices from November 2019 to September 2021, and found that the index exhibits weak form efficiency. Ahmetogulları (2024) analyzed the weak form efficiency in the BIST electricity sector and concluded that individual energy companies exhibit weak form efficiency, but the overall BIST Electricity Index shows mixed results. Ekmen and Evci (2024) examined weak-form efficiency in airline stocks on Borsa Istanbul and found that the stock prices of CLEBI, PGSUS, TAVHL, and THYAO exhibit unit roots, demonstrating that the weak-form efficient market hypothesis is applicable to them.

Ertaş and Özkan (2018) tested the AMH in Turkish and U.S. stock markets using monthly return data from the BIST 100 and S&P 500 indices. They found that the AMH can better explain stock market behavior than the EMH. Based on wild bootstrap automatic variance ratio tests, Özkan (2020b) found Brazil, South Africa, and Germany to be consistently weak-form efficient, while other markets' efficiency varied over time. Özkan (2020c) further supported this by examining the MIST countries (Mexico, Indonesia, South Korea, and Türkiye) and found that market efficiency evolves over time in response to changing market conditions. This confirms that return predictability is time-varying and consistent with the AMH. Aytekin and Dogan (2023) examined the validity of the AMH in Borsa Istanbul during major financial crises using sectoral and main indices. According to their findings, there are fluctuations in market efficiency depending on the type and duration of crises, supporting the hypothesis that efficiency varies over time.

Several studies have incorporated structural breaks and nonlinearities into tests of market efficiency. Altuntaş et al. (2022) used Fourier and nonlinear unit root tests to examine the efficiency of the weak form of six BIST indices and found mixed results. Demiralp and Belliler (2023) extended this

analysis to specific sub-indices and concluded that traditional unit root tests may produce biased results when nonlinearity exists.

Alkan (2024) investigated the relationship between liquidity and market efficiency in 397 stocks of the Borsa Istanbul by using the sample entropy. The study found that the stocks have different degrees of information complexity and illiquidity, which suggests that there is a strong relationship between liquidity and inefficiency.

Market efficiency can be adversely affected by external shocks, such as natural disasters and pandemics. Yıldıran (2021) analyzes the impact of COVID-19 on financial returns and market efficiency in Türkiye using BIST 100, sectoral indices, and currency returns and finds an initial decline followed by a recovery within 30 days. While ADF tests suggest weak form efficiency, the variance ratio test suggests inefficiency in the short run. Erer et al. (2023) investigated the time-varying efficiency of Turkish stock market and sectoral indices during the COVID-19 outbreak and the global financial crisis using multifractal detrended fluctuation analysis. In line with the adaptive market hypothesis, their results indicate that sectoral returns were more persistent during COVID-19, with the real estate and information technology sectors showing the lowest efficiency. According to Aksoy and Akyüzlü (2024), the Earthquake of 2023 had a significant impact on the Borsa Istanbul by causing significant abnormal returns in the Insurance and Non-Metal Mineral Product sectors. Similarly, Süsay Alkan (2024) examined how foreign and domestic investors affected Borsa Istanbul market efficiency during the COVID-19 pandemic and found that foreign investors positively enhanced market efficiency while domestic investors negatively affected market efficiency. Scalamonti (2025) used statistical techniques such as variance ratio tests and Hurst exponent analysis to analyze the weak-form efficiency of MEDA's capital markets, including Türkiye. According to the findings, institutional inefficiencies and exogenous shocks cause these markets to deviate from EMH.

The details of the studies on the efficiency of the Turkish stock market are given in Table 1.

Table 1. Overview of the EMH Literature on the Turkish Stock Market

Study	Data	Methodology	Series	Results
Duman Atan et al. (2009)	03.01.2003-30.12.2005	Unit root tests and Exact Local Whittle (ELW) estimator	XU100	efficient
Çevik and Erdoğan (2009)	2003 -2007 (Daily data)	Structural break test and long memory models	BIST Banking	not efficient
Çevik (2012)	03.01.1997-27.05.2011	Parametric and semi parametric long memory models	BIST Sector indices	not efficient
Zeren et al. (2013)	01.11.1987-30.11.2021	Structural breaks unit root tests	XU100	efficient
Gözbaşı (2014)	02.01.2004–07.03.2014 (Daily), 21.12.2009–07.03.2014 (Hourly)	Nonlinear unit root tests	XU100	efficient
Tanrıöver and Çöllü (2015)	01.1990-06.2014 (monthly)	Ljung-Box and LM analysis	XU100	not efficient
Malcıoğlu and Aydın (2016)	03.07.2000-22.09.2015	Harvey linearity test	XU100 and BIST Sector indices	not efficient

(Table 1 cont.)

Study	Data	Methodology	Series	Results
Yücel (2016)	2000-2015 (Daily)	Unit root tests	BIST indices	efficient
Ayaydın et al. (2018)	31.01.1997-27.01.2017 (weekly)	Harvey linearity test	XU100	not efficient
Bektur and Aydın (2019)	30.06.2000-29.12.2017	Unit root tests and Fourier unit root test	XU100 and BIST Sector indices	efficient
Özkan and Çakar (2020)	2014-2020	Autocorrelation analysis	BIST Islamic indices	Weak-form efficiency with deviations
Karademir and Evci (2020)	11.2008–11.2018	Unit root tests and structural break unit test	BIST Sector indices	efficient
Özkan (2020a)	2000-2020	Automatic portmanteau test	BIST sectoral indices	Varies by sector
Şahin (2020)	2008–2019 (Daily)	Run test	XU100, Dollar Exchange Rate and Gold Prices	not efficient
Altunöz (2020)	2004-2019 (monthly)	Structural break unit tests	BIST Sector indices	not efficient
Yıldıran (2021)	2020 (COVID-19 period)	ADF and Variance Ratio Test	BIST 100 & currency returns	Short-term inefficiency
Bal et al. (2021)	03.01.2005-28.12.2018	Unit root test and Fourier unit root test	BIST Baking	efficient
Aytekin et al. (2021)	15.02.2019-20.03.2020	Event study	XU100 and XU30 companies	not efficient
Altuntaş et al. (2022)	2010-2022	Fourier & nonlinear unit root tests	Six BIST indices	Mixed results
Dallı and Uğur (2022)	2019-2021 (Monthly)	Unit root and variance ratio tests	BIST Food & Beverage Index	Efficient
Özkan (2022)	2022 (Russia-Ukraine Conflict)	Volatility analysis	BIST	Increased inefficiency and volatility
Demiralp and Belliler (2023)	2015-2023	Nonlinear unit root tests	BIST sub-indices	Nonlinearity affects efficiency
Erer et al. (2023)	2008-2022	Multifractal detrended fluctuation analysis	BIST sectors	Efficiency varies across crises
Sakınç and Sakınç (2023)	2021-2023	Unit root and runs test	BIST Participation Indices	Not efficient
Alkan (2024)	2022-2024	Sample entropy	397 BIST stocks	Liquidity impacts efficiency
Aksoy and Akyüzlü (2024)	2023	Event study	BIST Insurance & Non-Metal Mineral Product indices	Abnormal returns after the earthquake
Ahmetoğulları (2024)	2015-2024	Unit root tests	BIST Electricity	Mixed results
Ekmen and Evci (2024)	2014-2024	Unit root tests	BIST Airlines	Weak-form efficiency
Süsay Alkan (2024)	2020-2021	Fourier cointegration	BIST 100	Foreign investors improve efficiency; domestic reduce it

3. METHODS

3.1. Sample Entropy

Traditional market efficiency tests, such as the Variance Ratio Test, Runs Test, and Augmented Dickey-Fuller (ADF) Test, rely on a binary classification framework, determining whether a market is either efficient or inefficient. However, these methods are limited in their ability to provide a continuous measure of efficiency, as they only confirm or reject the presence of a random walk. Financial markets, particularly emerging ones, often exhibit complex, nonlinear behavior that evolves over time due to external shocks, investor sentiment, and policy changes. Traditional statistical tests, which are based on

linear assumptions, often struggle to detect hidden dependencies and structural breaks, making them less effective in capturing the true dynamics of market efficiency. Additionally, these methods typically require stationary data and large sample sizes, making them unreliable when applied to volatile or short time-series datasets.

To overcome these limitations, Sample Entropy (SampEn) is employed in this study as a more flexible and adaptive approach. Unlike traditional methods, SampEn quantifies the degree of randomness and complexity in stock price movements, providing a continuous measure of efficiency rather than a binary classification. This allows for a more nuanced analysis, where efficiency levels can be tracked over time, revealing gradual shifts rather than abrupt categorizations. Moreover, SampEn is robust to noise and nonlinearity, enabling it to detect subtle patterns in financial time series that would otherwise be missed by conventional tests. Given these advantages, SampEn serves as an effective tool for assessing time-varying efficiency in financial markets, making it particularly suitable for studying the Borsa Istanbul and its response to market fluctuations, crises, and structural shifts.

Sample entropy measures the level of complexity and regularity of a time series. This method was primarily applied to examine the short and noisy signals in the field of biomedicine (Richman & Moorman, 2000). SampEn provides a non-negative numerical value for a given time series, where higher scores indicate a greater level of apparent randomness in the data. Conversely, lower scores suggest a greater presence of recognizable patterns within the data. A time series with many repeating samples will result in a comparatively small SampEn value, while more complex and unpredictable processes will produce higher values.

Let $x = \{x_1, x_2, \ldots, x_N\}$ be a time series of N points. Fix input parameters m and r, where m is the length of sequences to be compared, and r is the tolerance for accepting matches. The SampEn of the time series is calculated as below (Richman & Moorman 2000).

Construct the m-dimensional template vectors $\boldsymbol{x_m(i)}$:

$$x_m(i) = \{x_i, x_{i+1}, \ldots, x_{i+m-1}\}, \;\; 1 \le i \le N - m + 1 \tag{1}$$

Compute the distance between $x_m(i)$ and $x_m(j)$ using the Chebyshev metric (the maximum difference in their respective scalar components):

$$d\big(x_m(i), x_m(j)\big) = \big||x_m(i), x_m(j)|\big| = max\big\{\big|x_{i+k} - x_{j+k}\big| : 0 \le k \le m-1\big\},$$
$$1 \le i, j \le N - m + 1, j \ne i \tag{2}$$

Two vectors $x_m(i)$ and $x_m(j)$ are called m-dimensional template match if the distance $d\big(x_m(i), x_m(j)\big)$ is less than r. Let $n_i^m(r)$ be the number of vectors $x_m(j)$ within r of $x_m(i)$, without allowing self-counting. In the same way, let $n_i^{m+1}(r)$ present the number of vectors $x_{m+1}(j)$ within r of $x_{m+1}(i)$ for the vectors of length m+1, without allowing self-counting.

Then SampEn is given by the equation:

$$SampEn(m, r, N) = ln\left(\frac{\sum_{i=1}^{N-m} n_i^m(r)}{\sum_{i=1}^{N-m} n_i^{m+1}(r)}\right) \quad (3)$$

3.2. Multiscale Sample Entropy (MSE)

MSE is an extension of SampEn developed by Costa et al. (2002) to quantify the complexity of time series data at multiple timescales simultaneously. MSE provides a more comprehensive view by analyzing how regularity varies when the time series is evaluated at multiple scales, as opposed to sample entropy, which measures the irregularity of a single time series at one scale.

In the MSE analysis, the original time series is first partitioned into separate windows of length X, and then the average of the data points within each window is calculated. Each element of the coarse-grained time series $\boldsymbol{y^s}$ is determined as:

$$y_j^s = \frac{1}{s}\sum_{i=(j-1)s+1}^{js} x_i\,, 1 \le j \le \frac{N}{s}\,, \quad (4)$$

The SampEn is then calculated for each time scale using Eq. 3.

3.3. Relative Informational Efficiency Index

To further refine our analysis and ensure a standardized and comparable efficiency measure, we employ the Relative Informational Efficiency Index (RIEI), which normalizes SampEn values using Monte Carlo simulations of a pure random walk. This approach provides a relative efficiency score, allowing for direct comparisons across indices, sectors, and time periods, rather than relying on absolute entropy values that may vary due to sample-specific characteristics. By benchmarking against the maximum entropy observed in Monte Carlo simulations, RIEI allows for a more refined classification of market efficiency, distinguishing between varying degrees of efficiency rather than imposing a rigid efficient/inefficient classification.

Following the approach outlined in (Alvarez-Ramirez et al., 2012; Wang & Wang, 2021), the relative market efficiency index is calculated for each time scale s using the following formula:

$$I_{IME(s)} = \frac{MSE(s)}{\beta(s)} x100\% \quad (5)$$

where $\beta(s)$ denotes the upper bound for the entropy of Gaussian white noise. It is derived from 10,000 Monte Carlo simulations. If the entropy of index returns is below the entropy of Gaussian white noise (as determined by β(s)), or $I_{IME(s)} < 100\%$, it indicates that the market efficiency is only partial or fractional.

By integrating MSE and RIEI, this study moves beyond traditional efficiency assessments by providing a continuous, multi-scale, and standardized measure of market efficiency. This methodology

allows us to track how efficiency evolves dynamically and compare efficiency trends across different time periods and sectors, making it a more suitable approach for analyzing the time-varying nature of informational efficiency in Borsa Istanbul. The ability to detect partial efficiency states provides deeper insights into market behavior, making RIEI a novel contribution to the study of financial market efficiency, particularly in emerging markets where efficiency levels often fluctuate due to economic and structural shifts.

4. DATA AND PARAMETER SELECTION

In this study, we use the daily closing prices of the Borsa Istanbul composite index (XU100) and five major sector indices: Financials, Industrials, Services, Transportation, and Technology. In Table 2, these indices and the tickers associated with them are listed. The data span from January 2, 2017, to June 1, 2023, covering a total of 1,610 trading days. The chosen period provides sufficient data for rolling window analysis, which allows for a detailed examination of time-varying efficiency trends. It also includes major financial shocks such as the 2018 Turkish currency crisis, the COVID-19 pandemic (March 2020), the Russia-Ukraine conflict (2022), and the February 2023 earthquake, all of which had a significant impact on market dynamics.

Table 2. List of the indices with their associated tickers

Indices Name	Tickers
Borsa Istanbul composite index	XU100
BIST Financials	XUMAL
BIST Industrials	XUSIN
BIST Services	XUHIZ
BIST Transportation	XULAS
BIST Technology	XUTEK

These indices were chosen because they represent the main sectors of the Turkish stock market and show how the market works overall. Each sector index helps us understand how different parts of the economy react to market events and changes in the economy. By looking at both the whole market and its main sectors, the study aims to give a detailed and complete view of informational efficiency in Borsa Istanbul over time.

The daily logarithmic returns for each index are computed using the formula:

$$r_i(t) = \log P_i(t) - log\, P_i(t-1) \tag{6}$$

where $r_i(t)$ is the return for index *i* at time t, $P_i(t)$ and $P_i(t-1)$ are the closing prices on days *t* and *t-1*. Similar to Wang et al. (2012), returns are normalized by dividing $r_i(t)$ by $\sigma_i(t)$.

In accordance with previous studies (Richman & Moorman, 2000; Wang, et al., 2012), the length of sequences to be compared (m) is set to 2, and the tolerance range (r) is set to 0.25 times the standard deviation (σ) of the return series. To assess the efficiency at different time scales, we consider a range of 30 business days, which corresponds to six weeks.

5. EMPIRICAL RESULTS

The findings are presented in two distinct stages. Firstly, an evaluation of the Multiscale Entropy (MSE) and informational efficiency is conducted for each index throughout the entire sample period. Secondly, a rolling window technique is employed to investigate the time-varying nature of informational efficiency, enabling a comprehensive examination of how the efficiency levels of the indices evolve over time.

5.1. Informational Efficiency for Full Sample

Figure 1 displays the sample entropy estimates for scales up to 30 business days. It appears that the complexity of index returns is essentially dependent upon the time-scale s. There is generally a tendency for entropy to be higher at small time scales, while it declines at long time scales, indicating that reduction in pattern diversity and information content. The observed behavior indicates that the long-term return predictability of indices is relatively high as the entropy exhibits moderately small values at longer timeframes with coarse-graining procedure. The decline in entropy with higher time scales has been observed in previous studies using entropy methods for financial markets (Alvarez-Ramirez et al., 2012; Ortiz-Cruz et al., 2012; Wang & Wang, 2021). It should be noted, however, that XULAS and XUSIN show a local peak at the time scale of 20 days. This finding indicates that these indices were significantly influenced by information flows on a monthly basis.

Figure 1. MSE pattern across time scales

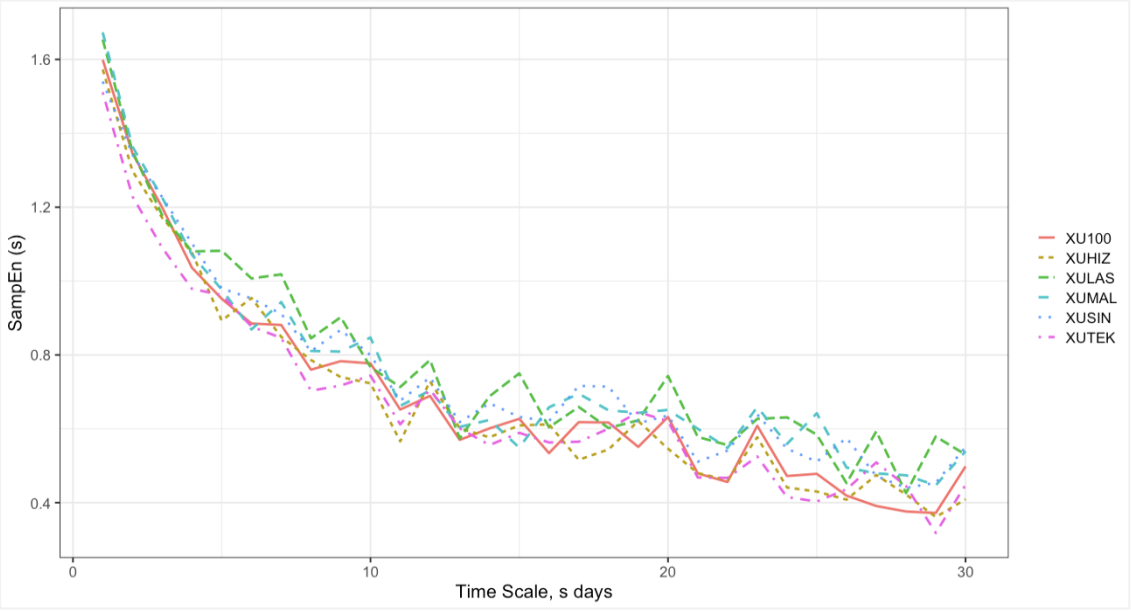


Figure 2. Relative informational efficiency index over time scales

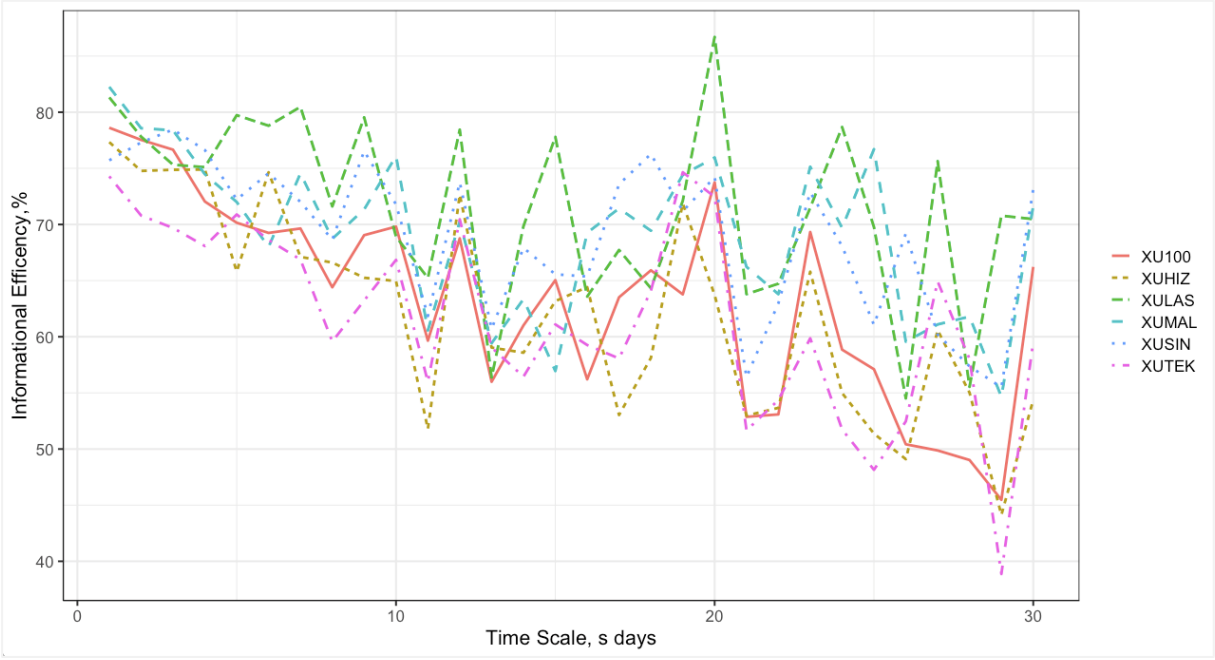


Figure 2 illustrates the relative informational efficiency of the indices over different time scales. The XUMAL Index has the most efficiency on a daily basis (82.25%), followed by the XULAS (81.32%), XU100 (78.61%), XUHIZ (77.34%), XUSIN (75.71%), and the XUTEK Index, which has the lowest efficiency (74.3%). There is a general trend of declining efficiency levels as the time scale increases. This implies that index returns cannot be fully characterized by purely random fluctuations, as evidenced by the decreasing number of entropy patterns observed with increasing time intervals. Instead, the indices exhibit partial efficiency, indicating deviations from perfect efficiency (100%) within certain time scales.

These findings illustrate that the market efficiency of the indices changes across different time scales, with some time scales showing higher efficiency levels than others. The findings suggest that there are factors influencing the behavior of the indices that lead to departures from full efficiency.

5.2. Time-varying informational efficiency

A rolling window procedure is used to study the fluctuations in market information efficiency over time. We split the dataset into M windows t=1, 2,..., M of width 252 daily returns (about one year) retained in the window, where successive windows were replaced by one trading day. Then, we calculate the informational efficiency for each index over a one-year period for each window.

Figure 3 illustrates the time-varying daily relative informational efficiency of the six indices. Several conclusions can be drawn from the figures. Firstly, they demonstrate the highly volatile nature of information efficiency levels across all indices, displaying a strong sensitivity to both the macroeconomic conditions within Türkiye and global events. This is in line with findings from Erer et al. (2023), who also observed time-varying efficiency in Turkish stock market sectors during financial

crises. During the period between 2018 and June 1, 2023, Türkiye's financial outlook underwent significant fluctuations and challenges. Numerous economic and political factors impacted the country's financial stability and performance.

In 2018, Türkiye experienced significant events such as the presidential election and strained diplomatic relations with the United States. The tightening monetary policy and interest rate hikes carried out by the Federal Reserve also influenced the flow of capital into stock markets, including Borsa Istanbul (BIST). Consequently, these factors contributed to a significant depreciation of the Turkish Lira and negatively affected BIST, resulting in it being categorized as a losing stock market. According to Table A2, both national and foreign investors experienced a decrease in their portfolio values, with a decline of 9.38% and 12.07% respectively.

In March 2019, local elections took place, followed by the repeat of Istanbul elections in June. Following periods after these elections, Borsa Istanbul's market capitalization showed improvement compared to the previous year. Moreover, the figures clearly indicate that the information efficiency of all indices exhibited an upward trend before the start of the COVID-19 outbreak.

Second, it is evident that all six indices encountered a sharp drop in efficiency in March 2020, when the World Health Organization (WHO) announced the COVID-19 outbreak as a pandemic. During the period from March 2nd to March 31st, the XUSIN Index experienced the largest decrease in informational efficiency, dropping by 17.29%. It was followed by XUHIZ with a decrease of 14.24%, XU100 with 11.3%, XUTEK with 10.72%, and XULAS with 8.91%. The XUMAL Index had the smallest decrease in daily market efficiency, with a drop of only 7.21%.

The average daily efficiency of the indices showed a significant decrease after March 2020. Prior to the pandemic, the XU100 index had the highest average market efficiency at 79.19%. It was followed by XUMAL with 77.95%, XUHIZ with 77.58%, XUSIN with 76.19%, XULAS with 75.15%, and finally XUTEK with the lowest average market efficiency of 65.89%. After March 2, 2020, the average market efficiency of the indices was as follows: XUMAL (67.89%), XUHIZ (66.38%), XU100 (65.7%), XULAS (64.27%), XUTEK (63.94%), and XUSIN (61.9). Comparing the two-period averages, the largest efficiency drops were observed for XUSIN (14.29%), XU100 (13.5%), XUHIZ (11.2%), XULAS (10.79%), XUMAL (10.06%), and XUTEK (1.94%). This study agrees with previous findings that extreme events can negatively affect market efficiency (Gaio et al., 2022; Lim et al., 2008; Ortiz-Cruz et al., 2012; Sensoy, 2013; Wang & Wang, 2021); however, the findings show that the extent of the impact appears to vary by sector.

The investigation has shown that the XULAS index attained its peak efficiency level of 82.29% on February 18, 2020. A steady decrease in efficiency was observed until December 10, 2020, when it reached its lowest efficiency level of 46.3%. As a precautionary measure, many countries and regions implemented quarantines, entry bans, or other travel restrictions due to the COVID-19 epidemic. As a

result of the restrictions, the travel industry has been adversely affected worldwide. In Türkiye, the financial performance of companies in this sector was negatively impacted by the pandemic.

During this period, the profitability of travel sector declined substantially and survived by financing from banks and other financial institutions (Alnıpak & Kale, 2021). Following the release of the news that the vaccines of Pfizer–BioNTech (November 9, 2020), Moderna (November 16, 2020), and AstraZeneca (November 23, 2020) were effective, the stock prices of passenger transportation companies indicated a bright outlook on the operating status of the companies and prospective earnings anticipations. As a result of the vaccine announcement, investors' panic and fear decreased, which contributed to a rise in the efficiency of the transportation sector as a result of optimism. Our finding is parallel to (Maneenop & Kotcharin, 2023; Martins & Cró, 2022) that a pandemic declaration harmed transportation stocks, while the announcement of vaccines had a favorable impact. However, unlike these studies, which focused on developed markets, our results highlight sectoral differences within an emerging market context. The transportation sector, in particular, experienced the largest efficiency decline, confirming previous research on the impact of pandemic-related travel restrictions (Alnıpak & Kale, 2021).

Overall, the results indicate the significant influence of external events, such as the COVID-19 epidemic and vaccine announcements, on the efficiency of the transportation industry within the Turkish stock market.

During the pandemic, the government implemented measures and programs designed to mitigate its effects and stimulate economic growth. The adoption of expansionary monetary policies led to a surge in the number of national investors participating in the stock market, resulting in a rapid rise in stock values. In response to the unusual price movements in the stock market during 2020, the Capital Markets Board of Türkiye and Borsa Istanbul implemented several measures. As a result, the trading volume of the Borsa Istanbul stock market increased significantly compared to the previous year (Turkish Capital Markets Association [TCMA], 2021). The high turnover rate in the stock market indicates liquidity but also suggests that investors have a short-term perspective when evaluating their portfolios. Since 2020, the portfolio values of national investors in Borsa Istanbul have surpassed those of foreign investors (Table A2). Furthermore, there has been a significant decrease in the holding period of foreign investors (Table A1). This shift in investment behavior can be attributed to increasing uncertainty, leading investors to adopt a short-term approach in evaluating their investments.

In 2021, due to the emergence of mutations and a rise in COVID-19 cases, lockdown measures were implemented in April and May. Within a span of 20 months, The Central Bank of the Republic of Türkiye (CBRT) witnessed four changes in its governor, with a new appointment made on March 20, 2021. From the third quarter of 2021 onwards, the CBRT began a gradual reduction of interest rates. Additionally, Türkiye experienced a currency crisis toward the end of 2021 that resulted in a sharp

depreciation of the Turkish lira against major currencies. In December, CBRT intervened directly in the market by engaging in selling transactions in response to distorted price formations in exchange rates. The crisis was triggered by a combination of factors, including persistent inflationary pressures, widening current account deficits, and mounting apprehensions surrounding the effectiveness of monetary policy.

Figure 3. Daily Market Efficiency

The outbreak of the Russia-Ukraine conflict in early 2022 led to a further drop in information efficiency across all indices, which reached even lower levels. Following the COVID-19 pandemic, the already low information efficiency levels experienced a slight decline with the occurrence of the February 2023 earthquake disaster in Türkiye. According to an evaluation of the entire period, it is evident that all indices, except XULAS, have not reached pre-COVID-19 levels of information efficiency. This suggests that the effects of the pandemic and subsequent events continue to impact the market's ability to effectively incorporate and reflect available information.

Table 3 provides descriptive statistics of the time-varying informational efficiency, aiming to enhance our understanding of the distribution of informational efficiency across the indices.

Table 3. Descriptive statistics of the time-varying informational efficiency

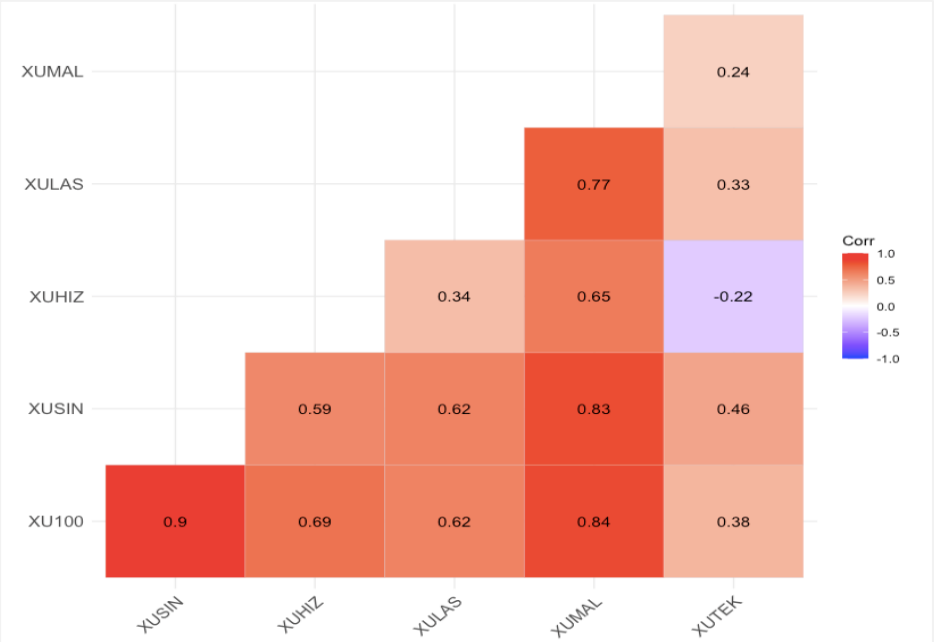
	XU100	XUSIN	XUHIZ	XULAS	XUMAL	XUTEK
Mean	71.10	67.62	70.87	68.59	71.92	64.72
Median	68.98	66.95	68.84	71.96	71.90	63.76
Maximum	89.93	90.59	90.26	82.66	82.33	87.55
Minimum	56.78	54.27	55.51	46.30	60.07	50.41
SD	7.82	8.50	7.53	8.52	5.82	7.82
Skewness	0.34	0.57	0.59	-0.84	-0.08	0.53
Kurtosis	2.10	2.39	2.35	2.81	1.72	3.11
JB p-value	0.00	0.00	0.00	0.00	0.00	0.00

Table 3 shows that XUMAL has the lowest standard deviation of the indices, followed by XUHIZ. In order to assess whether the observed time-varying informational efficiencies are influenced by random noise or adhere to a normal distribution, a normality test was conducted, the results of which strongly indicate a departure from normal distribution.

By considering the average of the calculated daily time-varying informational efficiencies, we can rank the indices accordingly. The findings reveal that XUTEK is characterized as the least efficient index in the Turkish stock exchange market, exhibiting relatively lower levels of informational efficiency. Conversely, XUMAL emerges as the most efficient index, showcasing higher levels of informational efficiency, followed by XU100.

A pairwise entropic correlation between two indices is used to evaluate the level of similarity between the informational complexity of the indices. In this context, entropic correlation is defined as the Pearson correlation between time-varying daily relative informational efficiency values (Stosic et al., 2016). Figure 4 displays the entropic correlation coefficients between any two indices. The range of correlation matrix values lies between -0.22 and 0.9. As can be seen, XU100 and XUSIN show the highest positive correlation, followed by XU100 and XUMAL, and then XUMAL and XUSIN indices, while XUTEK and XULAS indices have negative correlation. A weak correlation between the XUTEK and other indices suggests that there is little interaction between the XUTEK and other indices regarding information efficiency fluctuations. A high level of information efficiency in the XUMAL index may lead to higher correlations with other indices due to information spillovers.

Figure 4. Entropic correlation coefficient matrix of indices



6. CONCLUSION

The present research investigates the time-dependent nature of informational complexity and efficiency in the Turkish stock market for the BIST-100 and five major sector indices. The MSE-based method is implemented to measure market efficiency for 1 to 30 business days, and the rolling window technique is applied to investigate daily time-varying informational efficiency from January 2017 to June 2023.

Firstly, it is discovered that informational efficiency increased in all indices before the COVID-19 outbreak. Nonetheless, it is clear that all six indices experienced a sharp drop in efficiency in March 2020 after WHO classified the COVID -19 outbreak as a pandemic. During the period the XUSIN Index experienced the largest decrease in informational efficiency while the XUMAL Index had the smallest decrease in daily market efficiency. These findings support the studies that extreme events decrease the market efficiency (Gaio et al., 2022; Lim et al., 2008; Ortiz-Cruz et al., 2012; Sensoy, 2013; Wang & Wang, 2021).

Second, the application of severe measures to combat the spread of the virus resulted in a reduction in global economic activities and increased market uncertainty. The disruptions in production and trade, the slowdown in the service sector, and the prevailing atmosphere of panic and uncertainty all influenced investor behavior during this period. On the other hand, the vaccine announcements contributed to a decrease in investor panic and fear, leading to increased optimism and a rise in the efficiency of the transportation sector. This finding supports the studies by Maneenop and Kotcharin (2023) and Martins and Cró (2022), which state that the pandemic declaration had an adverse impact on transportation stocks, but vaccine announcements had a positive effect.

Third, during the pandemic, the implementation of expansionary monetary policies resulted in a spike in the number of national investors participating in the stock market, leading to a rapid surge in stock prices. Since 2020, the portfolio values of national investors in Borsa Istanbul have surpassed those of foreign investors. Furthermore, there has been a significant decrease in the holding period of foreign investors. This shift in investment behavior can be attributed to increasing uncertainty, leading investors to adopt a short-term approach in evaluating their investments. Although national investors have shown a high level of interest in the market, market efficiency has not returned to its pre-pandemic levels.

Finally, the occurrence of various events, including Türkiye's macroeconomic situation, the currency crisis, the Russia-Ukraine conflict, and the earthquake disaster, led to a further decrease in information efficiency, causing all indices, except XULAS, to fail in reaching their pre-COVID-19. The findings suggest that both the macroeconomic situation in Türkiye and global events impact the behavior of the indices, causing deviations from full efficiency. The notable reduction in efficiency observed during the COVID-19 pandemic and the Russia-Ukraine conflict is consistent with the results of previous studies. For instance, Gaio et al. (2022) and Özkan (2022) found that heightened volatility and uncertainty during crisis periods negatively impact market efficiency. Additionally, Aksoy and Akyüzlü (2024) reported that extreme events, such as earthquakes, trigger abnormal market responses and contribute to increased inefficiencies. These findings further reinforce and validate our results.

Our results support the Adaptive Market Hypothesis (AMH), which emphasizes that market efficiency changes depending on external events. Similar observations have been noted by Özkan (2020b, 2020c) and Aytekin and Doğan (2023), who found that market efficiency tends to fluctuate significantly during financial crises and geopolitical tensions. In contrast to earlier studies that typically examined individual crises separately, our research provides a broader perspective by analyzing multiple events, which includes the financial crises, geopolitical conflicts, a natural disaster, and prolonged economic instability. This approach helps reveal deeper patterns of efficiency reduction and underlines the importance of considering how different crises collectively affect investor behavior and market conditions. Such insights may be useful for policymakers aiming to enhance financial stability.

In this study, we provided valuable insights into Borsa Istanbul's time-varying efficiency; however, we must acknowledge certain limitations. We focused our research on five major industries, excluding subsector indices that may exhibit unique efficiency characteristics. Despite analyzing major crises such as COVID-19, the Russia-Ukraine war, inflation shocks, and earthquakes, the study does not take into account investor behavior at the micro level or effects related to high-frequency trading. In future research, intraday data could be explored, and cross-country comparisons carried out to determine whether these findings are unique to Türkiye or representative of a broader trend in emerging markets.

Ethics Committee approval was not required for this study.

The authors declare that the study was conducted in accordance with research and publication ethics.

The authors confirm that no part of the study was generated, either wholly or in part, using Artificial Intelligence (AI) tools.

The authors declare that there are no financial conflicts of interest involving any institution, organization, or individual associated with this article. Additionally, there are no conflicts of interest among the authors.

The authors affirm that they contributed equally to all aspects of the research.

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APPENDIXES

Table A1. Holding Period

Index	Nationality	2018	2019	2020	2021	2022
XU100	National	27	28	18	26	25
	Foreign	119	115	55	46	29
XUSIN	National	34	38	21	29	31
	Foreign	133	147	51	39	28
XUMAL	National	36	32	19	28	27
	Foreign	158	166	107	41	27
XUTEK	National	19	24	13	26	19
	Foreign	41	42	22	36	18
XUHIZ	National	25	22	14	22	24
	Foreign	111	109	63	64	35

Table A1 is obtained from the BIST Trends Report (January - December 2022) published by Turkish Investor Relations Society (2022).

Table A2. National and Foreign Portfolio Value

Year	National		Foreign		Portfolio weight of foreign investor (%)	Market Capitalization (Change %)
	Number of investors (Change %)	Portfolio Value (Change %)	Number of investors (Change %)	Portfolio Value (Change %)		
2011	5.26	-5.32	2.78	-20.74	62.16	-34.33
2012	-0.90	37.49	7.40	61.80	65.91	54.10
2013	1.91	0.49	15.07	-13.03	62.60	-23.65
2014	-3.21	22.82	2.83	30.29	63.97	13.53
2015	-1.49	-5.11	-0.92	-11.33	62.39	-29.52
2016	-1.74	6.12	-2.57	10.84	63.41	-8.24
2017	4.85	35.75	0.89	48.40	65.45	33.74
2018	8.12	-9.38	1.69	-12.07	64.76	-35.51
2019	2.10	67.19	-0.25	42.20	60.99	24.02
2020	65.61	104.97	23.25	24.54	48.71	28.72
2021	18.46	37.79	9.89	-3.87	39.85	-31.85
2022	60.83	249.83	29.63	118.72	29.29	102.77

The authors generated the Table A2 by utilizing data from the Central Securities Depository of the Turkish capital markets and Borsa Istanbul websites.