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CONTENTS

Journal of Sustainable Digital Futures 2025 1(1)

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Shaping sustainable digital futures: ICT, green growth, and ecological footprint

Betül ALTAY TOPCU[1]

HIGHLIGHTS

[1] Kayseri University, Vocational School of Social Sciences, Kayseri, Türkiye, batopcu@kayseri.edu.tr

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ABSTRACT

This study examines the impact of information and communication technologies (ICT) on environmental sustainability (ES) in Turkey from a green growth perspective over the period 1993-2022. For this purpose, two separate ARDL models were estimated. In the first model, individuals' internet usage was employed as the ICT indicator, while in the second model, mobile cellular subscriptions were used. In both models, the ecological footprint (EF) served as the environmental impact indicator, and green growth was included among the control variables. The results reveal that, in the first model, green growth and internet usage significantly reduce the EF. This finding suggests that internet usage, within the framework of green growth, can enhance energy efficiency and contribute positively to ES. In contrast, in the second model, the effect of mobile cellular subscriptions on the EF is negative but statistically insignificant. This indicates that the mobile communication infrastructure has not yet been utilized effectively in the context of ES or that its capacity to generate environmental benefits remains more limited compared to internet usage. These findings highlight the necessity of strengthening the environmental dimension in Turkey's digitalization policies. In particular, integrating mobile communication infrastructure into the green transition, supporting it with energy-efficient technologies, and aligning it with sustainable development goals are of critical importance.

1. Introduction

The diffusion of ICT has become a transformative force in shaping economic growth, social development, and ES. The environmental implications of ICT, particularly in relation to the EF, have attracted increasing scholarly attention in recent years. The EF serves as a comprehensive indicator that quantifies the biologically productive area required to support a population's consumption of natural resources and to absorb the waste it generates. ICT can influence the EF through dual channels: by enabling resource-efficient and low-carbon processes, thereby reducing environmental pressures, or by increasing energy demand through the expansion of digital infrastructures, which may exacerbate environmental degradation if powered predominantly by fossil fuels (Hassan et al. 2023).

From a theoretical standpoint, ICT has significant potential to mitigate EF by enhancing efficiency in production and consumption processes. Digital applications such as smart energy management systems, supply chain optimisation, remote working technologies, and advanced environmental monitoring tools can substantially reduce energy and material consumption. When integrated with renewable energy systems, ICT infrastructure can contribute to curbing the environmental impacts of carbon-intensive industrial activities (Kahouli et al. 2022; Qayyum et al. 2024). However, the rapid growth in ICT usage may simultaneously increase electricity demand for data centres and telecommunication networks, potentially offsetting environmental gains, particularly in economies reliant on carbon-intensive energy sources (Bonab et al. 2024).

ICT has the potential to reduce the EF by enabling the adoption of environmentally friendly technologies, increasing energy efficiency, and expanding digitalization in the context of green growth (Zhang et al. 2025). However, the ICT sector's high energy consumption, the carbon intensity of data centers, and increasing e-waste issues can have amplifying effects on the EF (Ozpolat, 2022). Therefore, within the theoretical framework, the impact of ICT on the EF is considered conditional and bidirectional.

The level of economic development and the structure of energy systems play a pivotal role in determining the nature of the ICT-EF nexus. Comparative evidence provided by Huang et al. (2022) for the E-7 (developing) and G-7 (developed) economies reveals that ICT's EF-reducing effects are more pronounced in developed countries. This can be attributed to the adoption of cleaner energy sources, advanced technological standards, and stricter environmental regulations in developed economies. By contrast, in developing economies, the environmental benefits of ICT may be constrained by dependence on fossil fuels for electricity generation. Institutional quality emerges as another critical determinant in the ICT-EF relationship. Studies by Opoku-Mensah et al. (2024) and Qayyum et al. (2024) demonstrate that ICT adoption, when supported by robust environmental governance mechanisms, can reduce EF even under conditions of policy uncertainty. Similarly, Mehmood et al. (2022) highlight that in G11 countries, the combined effect of ICT, renewable energy deployment, and sound governance significantly strengthens ES outcomes.

The relationship between ICT and EF may also exhibit asymmetry. Raza et al. (2023), using the QARDL approach, reveal that ICT's environmental impact is relatively limited at low levels of adoption but becomes significantly footprint-reducing once ICT diffusion surpasses a critical threshold. This suggests that scale effects are essential for realising the full environmental benefits of digital technologies. Urbanisation patterns further moderate the ICT-EF nexus. Kongbuamai et al. (2023) find that in Next-11 countries, the footprint-reducing potential of ICT can be undermined by rapid urban expansion, which drives up overall energy demand and places additional strain on urban infrastructure. Country-specific and regional studies provide further evidence of heterogeneity. Ozpolat (2022) finds that internet usage reduces EF in G7 countries, whereas Caglar et al. (2021) show that in the top ten footprint-intensive countries, ICT and renewable energy jointly contribute to environmental quality improvements. Kazemzadeh et al. (2023) extend the analysis to emerging economies, revealing that the environmental implications of ICT are mediated by socioeconomic variables such as fertility rates and economic complexity. In advanced economies, ICT's influence on EF is often amplified by technological innovation capacity. Onwe et al. (2025) report that ICT, in combination with advanced technological innovations and higher economic complexity, plays an integral role in driving sustainable climate action. This finding underscores the strategic importance of digitalisation not only for economic efficiency but also for the successful implementation of low-carbon development strategies.

This study aims to examine the effects of ICT on ES in Turkey from a green growth perspective. The primary motivation for this study is the limited literature addressing the environmental impacts of ICT in Turkey. Existing research largely focuses on developed countries, preventing a sufficient understanding of the impacts of ICT on ES in developing countries like Turkey. Therefore, examining the role of ICT use on environmental indicators in the Turkish context is crucial both to fill the gap in the literature and to provide new findings that can guide policymakers.

Covering the period 1993-2022, the analysis estimates two separate ARDL models to comparatively evaluate the environmental impacts of different dimensions of digitalization. In the first model, individuals' internet usage is employed as the ICT indicator, while in the second model, mobile cellular subscriptions are used. The EF is selected as the dependent variable, with green growth included as one of the control variables. The study makes three main contributions to the literature. First, it analyzes the environmental impacts of ICT in the Turkish context through the EF indicator, focusing not only on carbon emissions (CE) but also on the pressures on biological capacity. Second, it separately evaluates internet usage and mobile subscriptions, thus providing a comparative assessment of the effects of different components of digitalization on environmental performance. Third, by applying the ARDL method, it identifies long-run effects, offering practical implications for policymakers.

The findings reveal that internet usage, together with green growth, reduces the EF, while mobile subscriptions have a negative but statistically insignificant effect. These results indicate that internet technologies hold substantial potential for enhancing energy efficiency, promoting environmentally friendly practices, and supporting sustainable development. In contrast, mobile communication infrastructure does not appear to be utilized in a way that maximizes environmental benefits. Accordingly, strengthening the environmental dimension in Turkey's digitalization strategies-particularly by integrating mobile communication technologies into the green transition and supporting them with energy-efficient infrastructure-emerges as a key policy priority.

2. Literature review

This study aims to fill a gap in the literature by analyzing the impact of ICT on the EF within the context of green growth. The study also employs two different models: the first uses internet usage as an indicator of ICT, and the second uses mobile cellular subscriptions. This approach distinguishes the study from previous studies by examining the environmental impacts of ICT from different perspectives. The existing literature is examined under two headings: the impact of ICT on CE and the impact on the EF.

2.1. Relationship between CE and ICT

The impact of ICT on environmental quality has been addressed in the literature from multiple perspectives. Chen et al. (2019), using a quantile regression approach, investigated the potential of ICT to reduce CE and found that this effect is more pronounced in countries with high emission levels. Similarly, Anser et al. (2021), employing a panel quantile regression, concluded that ICT plays a mitigating role in CE, although the magnitude of this effect varies according to income levels and technological capacity.

Haseeb et al. (2019) examined the influence of ICT on environmental quality in the context of globalization and reported that ICT enhances energy efficiency and reduces CE. Shobande and Ogbeifun (2022), in their dynamic panel analysis for OECD countries, also found that ICT improves environmental quality, with limited short-term effects but more significant long-term benefits.

Hao et al. (2022) highlighted that ICT boosts green total factor energy efficiency, thereby indirectly reducing CE-a process strengthened by environmental regulations. Khan et al. (2022), focusing on BRICS economies, revealed that ICT, together with innovation and renewable energy consumption, fosters environmental improvement. In the case of China, Cheng et al. (2019) showed that information technology reduces environmental pollution, particularly through industrial transformation.

Zafar et al. (2022) investigated the role of ICT and education in environmental quality within selected Asian countries, finding that ICT facilitates the transition to environmentally friendly technologies and lowers CE. Wang et al. (2022), studying China's Yangtze River Delta urban agglomeration, observed that ICT concentration helps reduce emissions, especially in urban clusters.

Regional studies reinforce these findings. Avom et al. (2020) reported that in Sub-Saharan Africa, ICT improves environmental quality mainly through the energy efficiency channel. Awad (2022), applying second-generation panel techniques for Africa, confirmed the positive role of ICT in enhancing environmental quality. Overall, global evidence suggests that ICT consistently contributes to reducing CE.

2.2. Relationship between ecological footprint and ICT

In the context of EF, ICT's effects are evaluated over broader and longer-term dimensions. Hassan et al. (2023) examined the relationship between ICT diffusion, environmental innovation, and natural resource use, concluding that ICT supports green growth and reduces EF. Huang et al. (2022) compared the effects of ICT, renewable energy, and economic complexity on EF in E-7 and G-7 countries, finding stronger positive impacts in developed nations than in developing ones.

Kahouli et al. (2022), in the case of Saudi Arabia, determined that ICT, combined with renewable energy and total factor productivity, reduces EF. Qayyum et al. (2024) studied MERCOSUR nations and found that ICT's positive effects are amplified when supported by strong institutional quality.

Opoku-Mensah et al. (2024), using a volatility-driven model, demonstrated that ICT and green institutional governance are critical for mitigating EF, even under policy uncertainty. Kongbuamai et al. (2023) explored Next-11 countries, showing that while ICT has positive environmental effects, rapid urbanization can counteract these benefits.

Studies on advanced economies yield similar conclusions. Ozpolat (2022) found that internet usage reduces EF in G7 countries, with effects varying by income level and energy structure. Mehmood et al. (2022) observed that in G11 countries, ICT, governance quality, and renewable energy consumption work synergistically to reduce EF. Kazemzadeh et al. (2023) reported that in emerging economies, ICT-together with fertility rate and economic complexity-significantly influences EF.

On the asymmetric side, Raza et al. (2023) employed the QARDL approach and showed that ICT's environmental benefits are limited at low levels of ICT development but become more substantial at higher levels. Caglar et al. (2021), focusing on the top 10 countries with the highest EF, confirmed that ICT and renewable energy consumption reduce EF. Bonab et al. (2024) emphasized the need for integrating ICT use with green computing strategies to mitigate the carbon footprint.

Finally, Onwe et al. (2025) evaluated the role of ICT, technological innovation, and economic complexity in advanced economies, arguing that ICT should be strategically planned alongside innovative technologies to achieve ES.

3. Econometric analysis

This study examines the impact of ICT on the EF in Turkey over the period 1993-2022. In this section, the dataset and econometric model are first introduced, followed by the econometric methodology and findings.

3.1. Dataset and econometric model

The details of the variables used in the study are presented in Table 1.

Table 1. Definition and sources of variables

Variables **Dependent Variable**	**Symbols**	**Data Source**	**Definition**
Ecological footprint	lnEF	GFN	gha per person
Independent Variables			
Individuals using the internet	lnINT	WDI	% of population
Mobile cellular subscriptions	lnMCS	WDI	per 100 people
Renewable energy supply	lnGG	OECD	percentage of energy supply
Economic Growth	lnGDP	WDI	GDP per capita (constant 2015 US$)

Note: WDI: World Development Indicators; GFN: Global Footprint Network

In this study, the impact of ICT on the EF was investigated within the framework of two models. In the first model, individual internet usage was employed as the ICT indicator, renewable energy supply as the green growth indicator, and GDP per capita as the economic growth indicator. In the second model, unlike the first, mobile cellular subscriptions, another ICT indicator, were included as an explanatory variable. This approach allowed for a comparison of the effects of two different ICT indicators on the EF across the two models. EF data were obtained from the GFN database, ICT and economic growth data from the World Bank's WDI database, and green growth data from the OECD database. The natural logarithmic forms of the variables were used in the analyses. The selection of dependent and independent variables in Model 1 and Model 2 was informed by the studies of Ngoa and

Song (2021), Jóźwik et al. (2023), Ullah et al. (2024), and Georgescu et al. (2025). The specifications of Model 1 and Model 2 are presented below:

$$\textbf{Model 1: } \ln EF_{i,t} = \beta_0 + \beta_1 \ln INT_{i,t} + \beta_2 \ln GG_{i,t} + \beta_3 \ln GDP_{i,t} + \varepsilon_{i,t} \quad (1)$$

$$\textbf{Model 2: } \ln EF_{i,t} = \beta_0 + \beta_1 \ln MCS_{i,t} + \beta_2 \ln GG_{i,t} + \beta_3 \ln GDP_{i,t} + \varepsilon_{i,t} \quad (2)$$

3.2. Methodology and findings

The study first presents the descriptive statistics of the variables. Subsequently, the stationarity of the variables was examined using the ADF unit root test to determine their order of integration. Finally, the ARDL approach was applied to test the long-run relationship between the variables and to estimate the long-run coefficients.

Table 2. Descriptive statistics

	lnEF	lnINT	lnMCS	lnGG	lnGDP
Mean	1.106	2.250	3.365	2.582	9.017
Median	1.147	3.445	4.450	2.583	9.011
Max.	1.247	4.423	4.661	2.936	9.550
Min.	0.858	-4.772	-1.917	2.247	8.560
Std. dev.	0.110	2.515	1.900	0.209	0.304
Skewness	-0.608	-1.358	-1.599	0.037	0.175
Kurtosis	2.233	3.773	4.263	1.833	1.679
Obs.	30	30	30	30	30

The descriptive statistics for the variables are provided in Table 2. According to Table 2, during the period 1993-2022 in Türkiye, the average EF was 1.106%, while the average number of internet users, average mobile cellular subscriptions, average green growth, and average economic growth rates were 2.250%, 3.365%, 2.582%, and 9.017%, respectively.

Table 3. ADF unit root test results

		ADF	
Variable		**Level**	**1st difference**
lnEF	**Intercept**	-1.784 (0.380)	-9.345 (0.000)
	Trend & Intercept	-4.031 (0.018)	-9.306 (0.000)
lnINT	**Intercept**	-3.823 (0.008)	-3.013 (0.049)
	Trend & Intercept	-4.163 (0.016)	-7.228 (0.000)
lnMCS	**Intercept**	-5.810 (0.000)	-9.303 (0.000)
	Trend & Intercept	-5.658 (0.000)	-7.115 (0.000)
lnGG	**Intercept**	-1.500 (0.519)	-4.923 (0.000)
	Trend & Intercept	-0.557 (0.974)	-5.458 (0.000)
lnGDP	**Intercept**	0.519 (0.984)	-5.550 (0.000)
	Trend & Intercept	-3.260 (0.096)	-5.431 (0.000)

In time series analyses, examining the stationarity properties of the series is essential to statistically evaluate the relationships between them. Stationarity tests are considered the first step in constructing time series models and play a guiding role in determining the applicability of cointegration relationships, long-run coefficient estimations, and causality analyses. Conducting regressions without these analyses may lead to the problem of spurious regression and invalidate the results (Ecevit and Cetin 2022).

In this study, the stationarity of the series was determined using the ADF unit root test, which is frequently employed in time series analyses. Table 3 below presents the ADF unit root test results for the variables.

When the ADF unit root test results are evaluated for the constant model, the lnEF, lnGG, and lnGDP series are stationary at the first difference, while the lnINT and lnMCS series are stationary at both the level and the first difference. On the other hand, the ADF unit root test findings for the constant and trend model indicate that all variables except lnGG are stationary at both the level and the first difference. Only the lnGG variable exhibits an I(1) process.

Since the series in this study are stationary at different orders, the ARDL approach developed by Pesaran et al. (2001) was employed. The ARDL bounds testing method proposed by Pesaran et al. (2001) is widely used to determine cointegration relationships among variables. This method offers several advantages, such as being applicable regardless of whether the series are I(0) or I(1), providing valid results in small samples, and enabling the simultaneous evaluation of short- and long-run relationships through an error correction model (Eryer 2024). Before proceeding with the ARDL analysis, it is necessary to determine the lag length using the VAR model. As shown in Table 4, the appropriate lag length for both models is 1.

Table 4. Appropriate lag length of the VAR model

Lag Length (Model 1)	**LR**	**FPE**	**AIC**	**SIC**	**HQ**
0	NA	2.10e-06	-1.720167	-1.529852	-1.661985
1	210.5480*	7.09e-10*	-9.731569*	-8.779994*	-9.440663*
2	15.58987	1.06e-09	-9.409231	-7.696397	-8.885601
Lag Length (Model 2)	**LR**	**FPE**	**AIC**	**SIC**	**HQ**
0	NA	1.61e-06	-1.988911	-1.798596	-1.930730
1	239.2814*	1.55e-10*	-11.24959*	-10.29802*	-10.95869*
2	17.09200	2.14e-10	-11.00631	-9.293479	-10.48268

Note: * indicates lag order selected by the criterion

In the models estimated by considering the appropriate lag length for the variables, the F-statistic value is compared with the critical value table proposed by Pesaran et al. (2001). If the F-statistic is greater than the critical values, it indicates the presence of a long-run relationship among the variables. Conversely, if the F-statistic is lower than the critical value, it suggests the absence of a long-run relationship among the variables (Sarı and Yıldırım 2022). According to the ARDL bounds testing results presented in Table 5, the F-statistic value for Model 1 (9.949) and Model 2 (14.077) both exceed the upper bound critical value at the 1% significance level, indicating the existence of a long-run relationship among the variables.

Table 5. F-test results for cointegration

F-Bounds Test	**Model 1: F (lnEF/lnINT, lnGG, lnGDP)**
ARDL Model	(1, 0, 0, 1)
ECT_{t-1}	-1.014*
F-statistics	9.949*
F-Bounds Test	**Model 2: F (lnEF/lnMCS, lnGG, lnGDP)**
ARDL Model	(1, 1, 1, 1)
ECT_{t-1}	-1.065*
F-statistics	14.077*

Note: * denotes significance at the 1% level.

In the models, (ECT_{t-1}) represents the error correction term. A coefficient that is statistically significant and falls between 0 and –1 implies that short-run disequilibria are corrected over time (Cetin and Seker 2014). Examining the (ECT_{t-1}) terms for both models reveals that the error correction coefficients are negative and statistically significant at the 1% level. Therefore, the findings indicate that the error correction models are valid and functioning properly. This implies that short-run deviations will be eliminated in the long run (Coskun and Eygu 2020).

The long-run coefficient estimates in this study were obtained using the ARDL approach. To assess the reliability of the estimated models, a series of diagnostic tests were conducted,

Table 6. Long-run estimation results of the ARDL model and diagnostic tests

Variables	Coefficient	t-statistics	Prob.
	Model 1		
Constant	-1.496	-4.379	0.000
lnINT	-0.013	-1.808	0.083
lnGG	-0.225	-5.002	0.000
lnGDP	0.354	7.747	0.000
R^2	0.932		
Adjusted R^2	0.917		
F-statistics	63.420		0.000
	Diagnostic Test Results		
Breusch-Godfrey LM test	0.222		0.802
Breusch-Pagan-Godfrey	1.324		0.288
J-B Normality Test	0.274		0.871
Ramsey Reset Test	1.740		0.182
	Model 2		
Constant	-1.534	-6.265	0.000
lnMCS	-0.002	0.327	0.746
lnGG	-0.285	-6.552	0.000
lnGDP	0.370	11.535	0.000
R^2	0.954		
Adjusted R^2	0.938		
F-statistics	62.392		0.000
	Diagnostic Test Results		
Breusch-Godfrey LM test	0.096		0.908
Breusch-Pagan-Godfrey	0.576		0.767
J-B Normality Test	0.413		0.813
Ramsey Reset Test	1.558		0.230

For Model 1, the long-run estimation results from the ARDL bounds testing approach indicate that the variables lnINT and lnGG exert a negative and statistically significant impact on lnEF. Specifically, a 1% increase in internet usage reduces the EF by 0.013%, while a 1% increase in renewable energy supply reduces it by 0.225%. These results suggest that internet usage contributes to ES by enhancing energy efficiency and facilitating the dissemination of environmentally friendly practices. Similarly, the expansion of renewable energy supply lowers carbon intensity and alleviates pressure on natural resources. These findings are consistent with the results reported by Kongbuamai et al. (2023) and Opoku-Mensah et al. (2024) regarding the environmental quality-enhancing role of ICT.

However, the analysis also reveals that a 1% increase in lnGDP raises the EF by 0.354%, implying that economic growth, beyond a certain threshold, can increase environmental pressures and degrade environmental quality.

For Model 2, the long-run estimation results show that lnMCS has a negative but statistically insignificant impact on the EF. This suggests that mobile communication infrastructure has not yet been utilized effectively enough to deliver substantial environmental benefits, or that its contribution to ES remains more limited compared to internet usage. On the other hand, lnGG continues to have a negative effect, with a 1% increase in renewable energy supply improving environmental quality by 0.285%. This confirms that renewable energy supply is a key factor in enhancing environmental quality in both models. Furthermore, similar to Model 1, economic growth is found to increase the EF.

The diagnostic test results for both models indicate that the Ramsey RESET test confirms the correct functional form specification, the Jarque-Bera normality test shows that the residuals follow a normal distribution, the Breusch-Godfrey LM test suggests no autocorrelation problems, and the Breusch-Pagan-Godfrey test confirms that the homoskedasticity assumption is satisfied. These results demonstrate that the estimated models are statistically reliable and valid, and that the findings rest on a solid econometric foundation.

In the study, the stability of the coefficients was tested using the CUSUM and CUSUMSQ tests developed by Brown et al. (1975). As shown in Figure 1 and Figure 2, the test results indicate that, at the 5% significance level, the coefficients of the estimated models remained stable throughout the analyzed period.

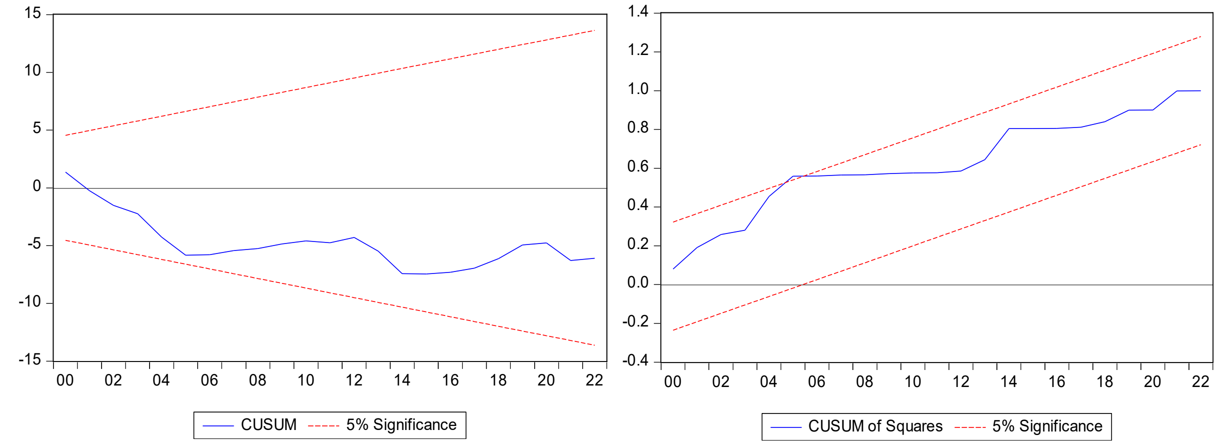

Figure 1. CUSUM and CUSUMSQ test results for Model 1

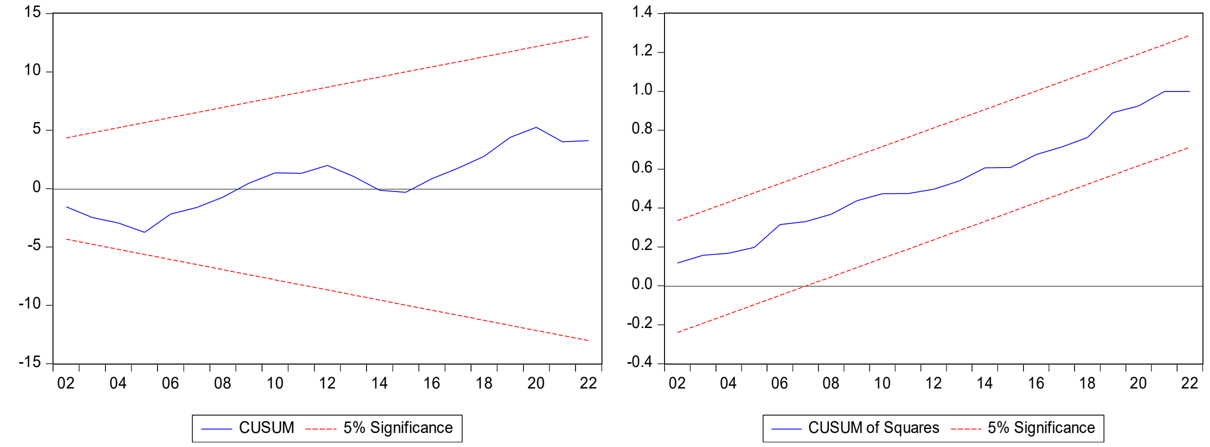

Figure 2. CUSUM and CUSUMSQ test results for Model 2

Table 7 presents the FMOLS and DOLS estimates conducted to assess the robustness of the ARDL long-run estimation results. As shown in Table 7, for Model 1, all estimation results are consistent with the ARDL findings. lnINT and lnGG reduce the EF, while lnGDP increases it. When the results are evaluated for Model 2, all estimations align with the ARDL results. In all estimations, the effect of lnMCS on environmental quality is negative but statistically insignificant. The influence of the other variables included in the model on environmental quality is similar to the ARDL results.

Table 7. FMOLS and DOLS estimation results

	FMOLS		DOLS	
Model 1	**Coefficient**	**Prob.**	**Coefficient**	**Prob.**
lnINT	-0.013	0.048	-0.016	0.005
lnGG	-0.239	0.000	-0.248	0.000
lnGDP	0.373	0.000	0.386	0.000
C	-1.610	0.000	-1.699	0.000
Model 2	**Coefficient**	**Prob.**	**Coefficient**	**Prob.**
lnMCS	-0.012	0.106	-0.005	0.733
lnGG	-0.233	0.000	-0.328	0.000
lnGDP	0.344	0.000	0.379	0.000
C	-1.354	0.000	-1.500	0.004

4. Conclusion and recommendations

This study investigates the effects of ICT on ES in Türkiye over the period 1993-2022, from the perspective of green growth. The primary objective is to analyze the impact of ICT on the EF and to comparatively assess the environmental effects of mobile cellular subscriptions and internet usage. To this end, two separate ARDL models were estimated, allowing for the identification of long-run dynamics. The findings reveal that the environmental implications of digitalization vary significantly depending on the ICT indicator considered.

In the first model, the relationships between individuals' internet usage, renewable energy supply, economic growth, and the EF were examined. The results indicate that both internet usage and renewable energy supply have a negative and statistically significant effect on the EF. This suggests that internet usage plays a crucial role in improving environmental quality by enhancing energy efficiency, facilitating the dissemination of environmentally friendly practices, and fostering public awareness of sustainability. In contrast, economic growth was found to exert a positive and statistically significant impact on the EF, implying that increases in per capita income tend to intensify resource consumption and environmental pressures. This finding is consistent with a study by Ozpolat (2022), who investigated the environmental impacts of internet use for G7 countries. Furthermore, it is consistent with a study by Akin and Ozgun (2024), who used the panel ARDL method to examine the impact of internet use on the environmental footprint of the "Fragile Five" countries (Brazil, India, Indonesia, South Africa, and Turkey), including Turkey.

The second model focused on the environmental effects of mobile cellular subscriptions. While the results show that mobile subscriptions have a negative but statistically insignificant impact on the EF, this finding suggests that mobile communication infrastructure is not yet being utilized effectively in the context of ES, or that its potential benefits for energy efficiency and resource conservation remain limited. Accordingly, Türkiye's digitalization strategies should prioritize the integration of mobile communication infrastructure with green growth policies and the adoption of energy-efficient technologies.

This finding is similar to a study by Edquist and Bergmark (2023). In their study examining CE from mobile broadband penetration for 181 countries, the authors found that mobile broadband use may initially increase CE, but this effect reverses. They found that this relationship is particularly evident in high-income, regular users. Furthermore, the developments by Fehske et al. (2010) emphasize that mobile communication products are affected by environmental temperature fluctuations and that energy-efficient technologies play a crucial role in supporting the growth of regional mobile communication. This finding, in contrast to the existing study, suggests that the temperature impacts of mobile infrastructure can vary depending on usage and technology intensity, particularly in Turkey, where mobile companies' activity impacts the footprint of their networks.

The empirical findings point to the need for a more integrated design of digitalization and green growth policies in Türkiye. In particular, enhancing the environmental benefits of internet usage and transforming mobile communication technologies to maximize environmental gains are of paramount importance. Policy priorities should include the establishment of green data centers, the integration of renewable energy sources into digital infrastructures, the promotion of environmentally friendly devices, and the adaptation of mobile network infrastructure to energy-efficient technologies.

In conclusion, a comprehensive evaluation of the environmental impacts of ICT is critical for enhancing the effectiveness of green growth strategies in line with sustainable development goals. The finding that internet usage contributes positively to ES demonstrates that digitalization, when guided by appropriate strategies, can serve as a development tool aligned with ecological objectives. At the same time, the untapped potential of mobile technologies in terms of energy efficiency, resource management, and environmental innovation underscores the importance of targeted interventions to leverage these benefits.

Limitations of this study include its exclusive focus on Türkiye, which constrains the generalizability of the results to countries with different economic and institutional contexts, the restriction of the dataset to the period 1993-2022, and the possibility that the selected ICT indicators do not capture all environmental dimensions of digitalization. Moreover, while the EF is a comprehensive environmental metric, it does not encompass every aspect of ecosystem impact. Future research could expand the analysis to cross-country comparisons, assess the environmental implications of emerging technologies such as artificial intelligence, the Internet of Things (IoT), and blockchain, and conduct sector-specific analyses (e.g., energy, agriculture, transportation) to develop more targeted policy recommendations.

Declaration of competing interest

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

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Trends in academic literature on the concepts of digitalization and sustainability

Servet SAY[1]

HIGHLIGHTS

[1] Selçuk University, Vocational School of Social Sciences, Konya, Türkiye, servetsay@selcuk.edu.tr

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ABSTRACT

This study aims to analyze the academic literature at the intersection of digitalization and sustainability through a bibliometric approach. A total of 2.513 documents obtained from the Web of Science database between 2007 and 2025 were examined and visualized using R Studio software at the levels of authors, countries, institutions, journals, and keywords. The findings reveal a significant increase in academic interest in the themes of digitalization and sustainability, particularly after 2018. Asian and European countries -especially China and India- play leading roles in this academic output. While the journal Sustainability hosts the largest number of publications, authors such as Barboni, B. and Compagnone, D. stand out in the literature. Keyword and trend analyses indicate that "digital transformation", "green innovation" and "supply chain digitalization" are emerging research themes. The study presents a systematic overview of the current state and future research directions of the digitalization-sustainability relationship within a multidisciplinary framework.

1. Introduction

With the evolution into an information society in the 21st century, digitalization and sustainability have emerged as two of the most frequently discussed concepts globally, both in academic and practical contexts. Digital technologies have triggered structural transformations in many areas, from production to consumption, and from governance to education, while sustainability represents a fundamental set of principles that ensure this transformation is achieved in a balanced manner across environmental, economic, and social dimensions. The joint consideration of these two concepts has gained increasing importance in the academic literature, particularly in questioning the extent to which digital transformation aligns with sustainable development goals (Bai et al. 2020).

Digitalization refers not only to a technological shift but also to a broader societal transformation characterized by data-driven decision-making processes, the proliferation of artificial intelligence applications, and the redefinition of business models through platform economies (Schallmo and Williams 2018). On the other hand, the concept of sustainability, as defined within the framework of the United Nations' 2030 Sustainable Development Goals (SDGs), aims to achieve not only environmental protection but also social equity and economic development in a holistic manner (UN 2015).

Studies situated at the intersection of these two concepts in the literature focus on various topics, including the environmental impacts of digital technologies (e.g., carbon footprint), green information systems, digital sustainability strategies, and organizational agility (ElMassah and Mohieldin 2020;

George et al. 2021). However, the growing volume of research, the wide array of contributions from different disciplines, and the fragmented nature of the literature point to the need for a systematic and quantitative analysis.

In this regard, bibliometric analysis provides a means of quantitatively evaluating trends, productivity, and collaborations in academic writing, thereby allowing for the systematic mapping of the topic (Donthu et al. 2021). In this study, academic works on digitalization and sustainability are visualized using R Studio software to uncover thematic connections between the two concepts, trace their development in the literature, and identify future research directions.

2. Conceptual framework

Digitalization refers to a socio-technical transformation process resulting from the integration of analog information and processes into digital technologies (Brennen and Kreiss 2016). This process encompasses not only the development of technological infrastructures but also the adaptation of institutions, societies, and individuals to digital environments and their interactions with digital tools. With advancements in information and communication technologies, digitalization has laid the groundwork for the widespread adoption of digital business models, particularly in sectors such as production, services, education, and healthcare. Supported by technologies such as Industry 4.0, big data, artificial intelligence (AI), cloud computing, and the Internet of Things (IoT), businesses and public institutions have become more agile, efficient, and customer-oriented (Vial 2019). Moreover, digitalization is increasingly regarded as a powerful tool for achieving sustainability goals (George et al. 2021).

Sustainability is a development approach that advocates for the responsible management of environmental resources in a way that meets the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable development is built upon three main pillars: environmental (nature conservation), economic (efficiency), and social (equity) (Purvis et al. 2019). Sustainability is not limited to environmental responsibilities; it also encompasses corporate governance models, business strategies, and public policies. Corporate sustainability strategies are commonly discussed across various disciplines, including the use of eco-friendly technologies, green supply chain management, and circular economy practices (Lozano 2015).

In recent years, the interaction between digitalization and sustainability has been conceptualized in the literature through terms such as "digital sustainability" and "green digitalization". These concepts explore how digital technologies can be utilized as instruments to advance sustainable development goals. Digital solutions are used to enhance energy efficiency, reduce greenhouse gas emissions, optimize resource consumption, and facilitate environmental monitoring (ElMassah and Mohieldin 2020). Furthermore, the benefits of digital tools in data collection, analysis, and decision-support processes contribute to increased transparency and accountability in public policy-making (Hilbert 2020). However, some critiques also highlight that digitalization may introduce new sustainability challenges, such as excessive energy consumption, electronic waste generation, and social inequality (Salahuddin et al. 2015).

Bibliometric analysis has made significant and positive progress over time, guiding researchers in a more comprehensive and effective measurement process. Bibliometric analysis technique, one of the qualitative research methods, is currently used in many different academic disciplines (Okuba 1997; Kınalı 2025).

In this context, a multidimensional evaluation of the impact of digitalization on sustainability requires the systematic analysis of relevant studies. Bibliometric analysis offers an effective method to identify how these two concepts are addressed in conjunction, the areas in which they intersect, and the topics that present research gaps (Donthu et al. 2021).

3. Methodology

This section presents the research objective, data collection process, limitations, and the analyses conducted. The primary aim of this study is to conduct a comprehensive bibliometric analysis of scientific research carried out within the conceptual framework of "digitalization" and "sustainability". Accordingly, the structure, development, trends, and collaboration networks of the relevant literature will be revealed through academic publications indexed in the Web of Science database. The dataset for the bibliometric analysis was obtained from the Web of Science (WoS) Core Collection database. This database is frequently preferred in bibliometric studies due to its access to high-impact and indexed publications in the academic field (Mongeon and Paul-Hus 2016).

The data collection was carried out on April 1, 2025, using the "All Fields" search option with the keywords "digitalization" and "sustainability". The selected time range was 2000-2024. Choosing a specific starting year was intended to capture the period during which these concepts began to show meaningful academic production (Donthu et al. 2021). R Studio software was used for the data analysis and visualization process. This programme was preferred because it allowed researchers to discover their evolution, relationships and new concepts in the literature. It also allowed for in-depth analysis of the data sets by providing visualisation, mapping and multidimensional analysis (Say et al. 2025). The dataset obtained from WoS was directly transferred into R Studio, and network maps were generated based on the filtering criteria offered by the software. Bibliometric analysis is a method that aims to numerically examine academic publications and thus evaluate elements such as scientific productivity, impact and collaboration. Powerful software tools are needed to carry out these analyses in a healthy manner. In this context, the R programming language stands out thanks to its open-source structure and packages developed for bibliometric analysis (Aria and Cuccurullo 2017).

This study is limited to publications included in the Web of Science Core Collection. Therefore, studies indexed in Scopus, Google Scholar, PubMed, or local databases were excluded from the analysis. Additionally, only publications written in English were considered. This creates a potential limitation in terms of fully representing the entire body of literature.

4. Findings

This section presents the findings obtained from the study. The data shown in Table 1 reveal the scope and structure of the bibliometric dataset that forms the foundation of the research. The documents examined cover an 18-year time span from 2007 to 2025. This broad timeframe provides a suitable framework for analyzing the temporal development of academic production in the field.

Table 1. Main information

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2007:2025
Sources (Journals, Books, etc)	837
Documents	2513
Annual Growth Rate %	37,18
Document Average Age	2,23
Average citations per doc	14,19
DOCUMENT CONTENTS	
Keywords Plus (ID)	3214
Author'‘s Keywords (DE)	7658
AUTHORS	
Authors	8460
Authors of single-authored docs	195
AUTHORS COLLABORATION	
Single-authored docs	200
Co-Authors per Doc	3,99
International co-authorships %	35,69

An examination of Table 1 reveals that the dataset comprises 2.513 documents sourced from a total of 837 different outlets, indicating a high volume of publications and a wide diversity of research within the field. The annual growth rate of 37.18% suggests that interest in this topic has been steadily increasing, positioning it as an emerging research theme. This trend points to the growing importance of the subject at both academic and practical levels.

An average of 14.19 citations per document demonstrates that the studies have achieved a certain degree of academic impact and have been well-received in the literature. Furthermore, the average document age of 2.23 years indicates that the dataset predominantly consists of recent publications, highlighting the fields openness to new developments.

In terms of authorship and collaboration, a total of 8.460 authors contributed to the publications, with an average of 3.99 authors per document. This finding suggests that research in the field is largely produced through collaborative efforts. The international co-authorship rate stands at 35.69%, reflecting that the topic is addressed not only at the local level but also globally, with widespread cross-border collaboration among researchers.

Figure 1 below presents the distribution of documents in the dataset according to their types.

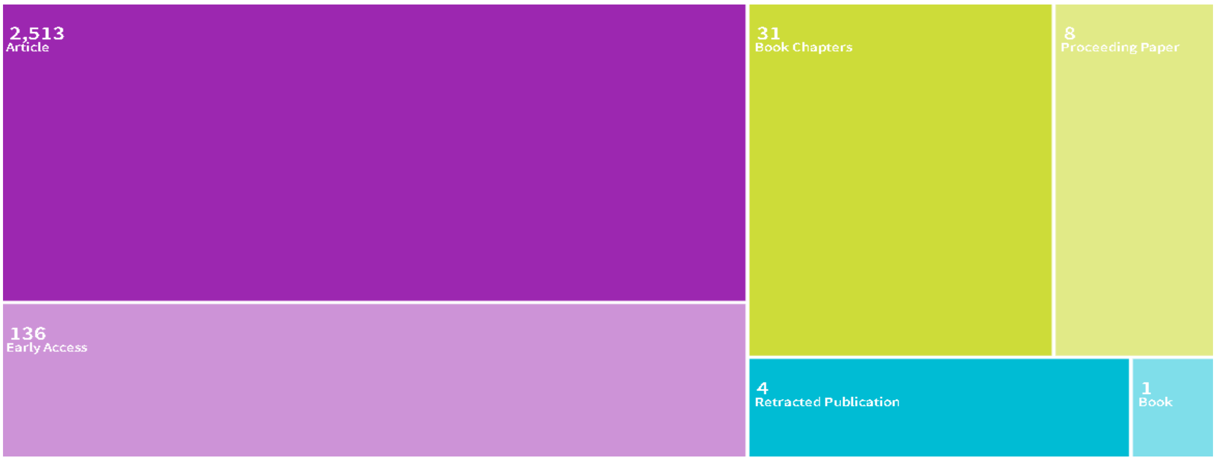

Figure 1. Document types

According to Figure 1, peer-reviewed journal articles (n = 2.513) constitute the majority of the documents analyzed in the study. This density indicates that the research topic is addressed within the academic community with a strong theoretical and empirical foundation. The presence of 136 early access publications further highlights the topical relevance of the field and suggests that research outputs are being rapidly disseminated into the scientific community. Additionally, other document types such as 31 book chapters and 8 conference papers are present in more limited numbers.

Figure 2 presents a Three-Field Plot that illustrates the relationships among affiliations, authors, and countries contributing to the research.

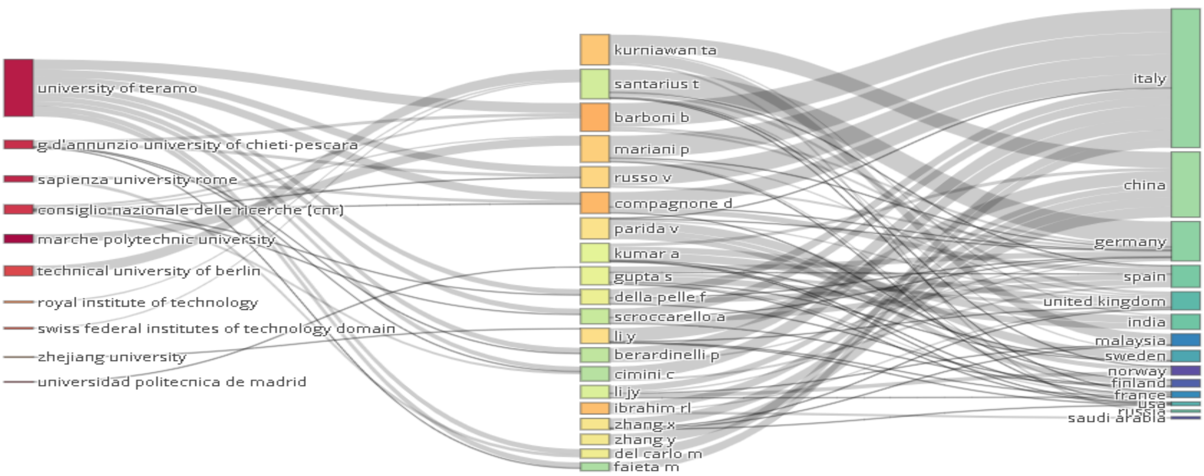

Figure 2. Three-field plot

According to Figure 2, a significant portion of the research is conducted by Italy-based affiliations such as the University of Teramo, G. D'Annunzio University of Chieti-Pescara, Sapienza University of Rome, and the National Research Council (Consiglio Nazionale delle Ricerche). Similarly, authors such as Kurniawanta, Santarius T., Barboni B., and Mariani P. stand out due to their high productivity.

At the country level, Italy clearly demonstrates leadership in publication volume, followed by countries such as China, Germany, Spain, and the United Kingdom. These findings indicate that strong international collaborations particularly between European and Asian countries are ongoing in this area of research.

Figure 3 displays the change in the number of articles published in various countries over time, starting from the year 2007. The data provide a comparative temporal analysis of countries' academic productivity.

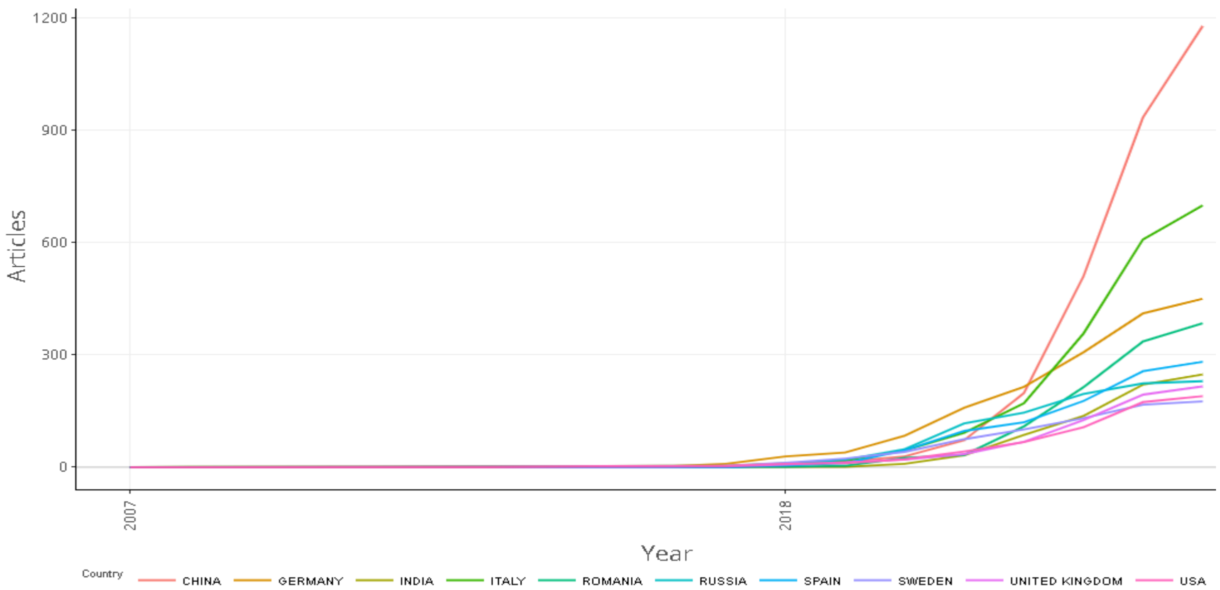

Figure 3. Countries' production over time

Figure 3 presents a comparative temporal analysis of countries' academic productivity. The countries examined include China, Germany, India, Italy, Romania, Russia, Spain, Sweden, the United Kingdom, and the United States.

Until 2018, article production remained relatively limited across all countries. However, a notable increase is observed after this point. In particular, China has shown a steady upward trajectory since 2019, clearly distinguishing itself from other countries and reaching approximately 1.200 publications by 2023-the highest output by far. This reflects China's rapid rise in the academic field and its increasing investment in the area.

India has also demonstrated a remarkable rise after 2019, reaching over 600 publications by 2023, placing it second. Germany follows these two countries, showing steady growth and ranking third with approximately 450 publications.

Italy, Russia, Spain, and the United States exhibit a moderate upward trend, while countries such as the United Kingdom, Sweden, and Romania display relatively more limited increases. These differences may be attributed to variations in national research infrastructures, funding mechanisms, and strategic priorities related to the field.

Figure 4 provides a comparative representation of the number of documents published in specific academic journals. The horizontal axis represents the number of documents, while the vertical axis represents the sources.

The data presented in Figure 4 show the academic journals with the highest number of publications related to the topic under study. According to the data, the journal "Sustainability" leads by a wide margin, with 749 documents published. This indicates that a significant portion of sustainability-themed research has been published in this journal, highlighting its role as a leading platform in the field.

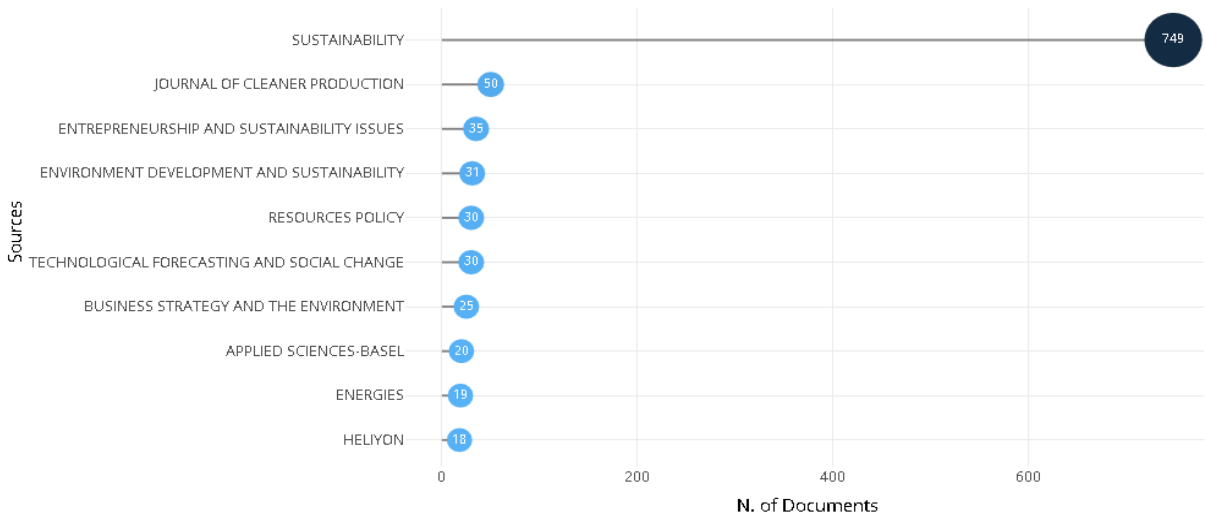

Figure 4. Most relevant sources

"*The Journal of Cleaner Production*" ranks second with 50 documents, followed by "*Entrepreneurship and Sustainability Issues*" in third place with 35 documents. Both journals are recognized for their focus on sustainable development, environmental efficiency, and clean production.

Other prominent journals include "*Environment, Development and Sustainability*" (31 documents), "*Resources Policy*" (30 documents), and "*Technological Forecasting and Social Change*" (30 documents), which concentrate on topics such as environmental management, resource utilization, and societal transformation.

Figure 5 illustrates the most prolific authors in this field and the number of documents they have published. The horizontal axis represents the number of documents published, while the vertical axis lists the authors.

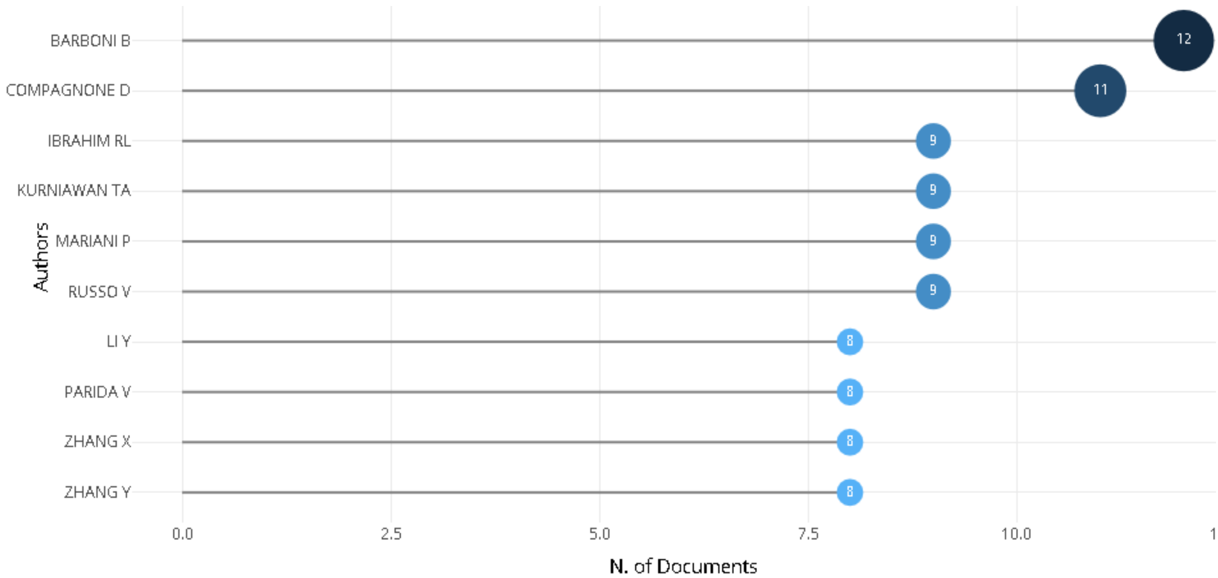

Figure 5. Most relevant authors

According to Figure 5, Barboni, B. is the most prolific author with a total of 12 publications. He is followed by Compagnone, D., with 11 publications. These two authors stand out as leading researchers in the subject area under investigation and have likely made significant contributions to the field both quantitatively and qualitatively.

Following these top two authors, Ibrahim, R.L., Kurniawan, T.A., Mariani, P., and Russo, V. each have 9 publications, indicating a focused publication strategy and consistent engagement with the topic.

Li, Y., Parida, V., Zhang, X., and Zhang, Y. complete the list with 8 publications each. These authors have also secured a notable place in the literature and appear to have strong potential for continued contributions to the field in the future.

Figure 6 presents a word cloud, visually representing the most frequently encountered keywords in a particular academic domain. The size of each word indicates the frequency of its use larger words represent more frequently used and more central terms.

Figure 6. Word cloud

The terms in the wordcloud clearly indicate that the concepts of sustainability and digitalization have been extensively studied. The most prominent terms include "Digital", "Digitalization", "Sustainable", "Sustainability", and "Development".

Figure 7 is a timeline visualization that illustrates the visibility of terms used in the literature over time, or when they became popular in research. The vertical axis lists the terms, while the horizontal axis represents the years. The size of each dot indicates the frequency or significance of the term's usage in a given year.

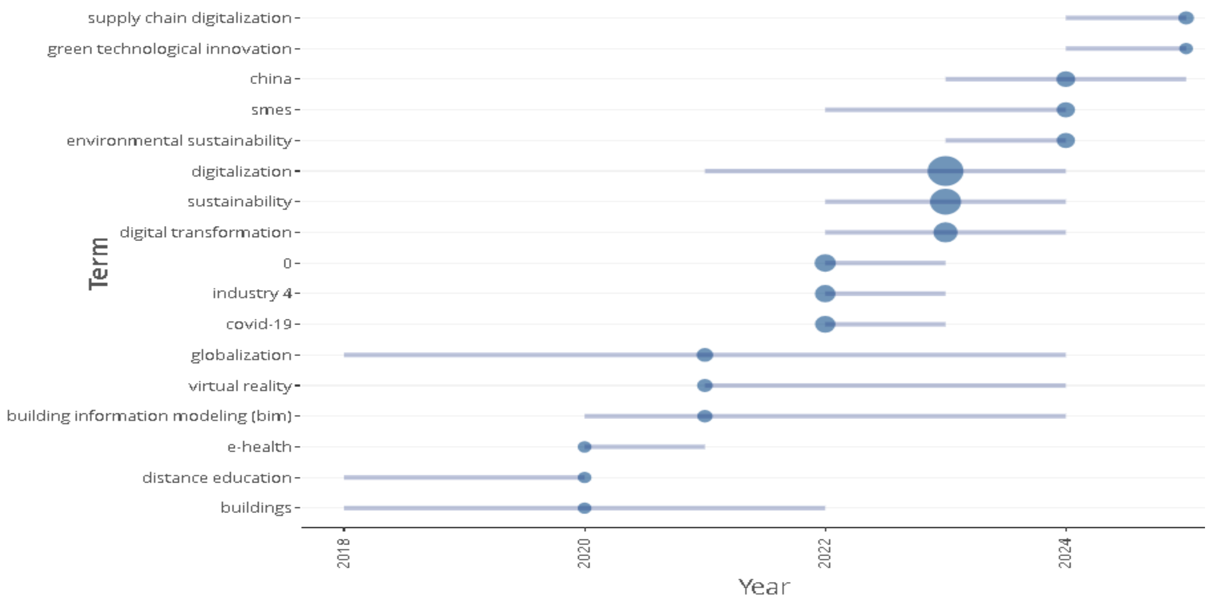

Figure 7. Trend topics

According to Figure 7, as of 2022, the most frequently used terms include "digitalization", "sustainability", and "digital transformation". In the 2023-2024 period, terms such as "green technological innovation", "supply chain digitalization", and "environmental sustainability" gained prominence.

Figure 8 below illustrates the collaboration network among researchers.

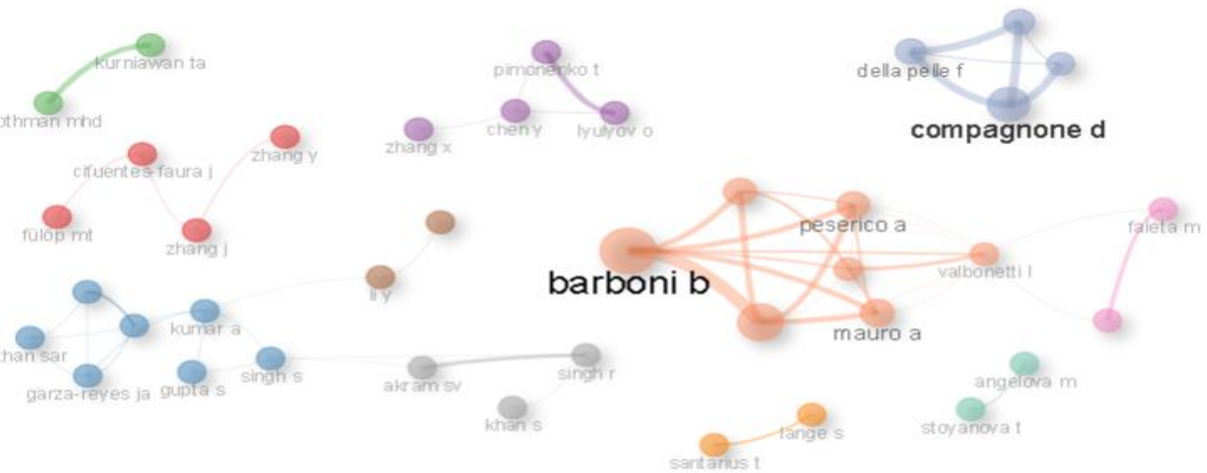

Figure 8. Collaboration network

This collaboration network demonstrates that certain key authors such as Barboni, B. and Compagnone, D. form central clusters in the literature and play pivotal roles in the field’s research productivity. At the same time, the presence of numerous smaller and relatively isolated collaboration clusters indicates that the research domain is highly decentralized and diverse.

5. Conclusion

This study presents a quantitative and visual analysis of academic output at the intersection of digitalization and sustainability, revealing trends, collaborations, and thematic concentrations within the field. Based on data obtained from the Web of Science database and analyzed using R Studio software, a scientific mapping of 2.513 documents published between 2007 and 2025 within the scope of these two concepts was produced.

An examination of publication trends by year shows a notable increase in productivity, especially after 2018, with countries such as China, India, and Germany standing out. China leads with approximately 1.200 articles as of 2023, indicating that digitalization and sustainability have become central topics on the global academic agenda.

The journal "*Sustainability*" was by far the most frequently preferred source, with 749 publications, followed by "*The Journal of Cleaner Production*" and "*Entrepreneurship and Sustainability Issues*". These journals demonstrate that research in the field is structured around the themes of sustainable development and digital transformation.

In the author analysis, Barboni B. and Compagnone D. emerged as the most productive researchers, with 12 and 11 publications respectively. Co-authorship network analyses revealed that clusters formed around these authors occupy a central position in the literature, indicating that academic leadership and collaboration in this field are concentrated within certain core groups.

The keyword analysis (Figure 6) and trend timeline (Figure 7) highlight that terms such as "digitalization", "sustainability", "digital transformation", and "green technological innovation" are dominant and have seen increased research interest particularly after 2022. The emergence of more application-oriented subthemes such as "supply chain digitalization" and "environmental sustainability" in recent years shows that digitalization is being increasingly integrated into sustainable development strategies.

Digitalization and sustainability are concepts that attract a high level of academic interest separately. However, comprehensive and numerical-based studies that address these two concepts together are limited. This study fills an important gap in the literature by systematically analyzing the literature shaped around the digitalization-sustainability axis. The research examines 2,513 academic publications obtained from the Web of Science database and covering the years 2007-2025. The wide time period and high number of documents increase the reliability and validity of the study; it comprehensively reveals the publication trends, especially the rapidly increasing ones after 2018. Since digitalization and sustainability are topics addressed in different academic disciplines, the bibliometric analysis presented in this study has been shaped by a multidisciplinary approach. In this respect, it contributes to both social sciences and technical sciences literature. This study provides a qualitative contribution to bibliometric analysis studies in the field of digitalization and sustainability in terms of its scope, method and approach to the subject; while mapping the current state of the literature, it also serves as a strategic guidance for future studies.

In conclusion, the analyses presented in this study demonstrate that digitalization and sustainability form an interrelated and multidisciplinary academic domain. Accordingly, future research should focus on evaluating the effectiveness of green digitalization policies, the environmental footprint of digital technologies, and data-driven sustainability strategies, which would contribute to the literature both theoretically and practically.

Declaration of competing interest

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

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The views expressed in this study are those of the author.

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The impact of digitalization and economic growth on sustainable environmental management in Asian countries

Murat TEKBAŞ[1], Ali Emin İSLAMOĞLU[2]

HIGHLIGHTS

[1] Afyon Kocatepe University, Afyon Vocational School, Afyonkarahisar, Türkiye, mtekbas@aku.edu.tr
[2] Kilis 7 Aralık University, Vocational School of Social Sciences, Kilis, Türkiye, alieminislamoglu@kilis.edu.tr

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ABSTRACT

The relationship among information and communication technology (ICT), economic growth, and environmental pollution has gained increasing importance in recent years. This study examines the linkage between CO2 emissions, economic growth, and digitalization for the period 2001-2022 using a panel of 15 countries with comparable data that together represent approximately 50% of the world population. Stationarity of the series was assessed with Levin-Lin-Chu (LLC) and Im-Pesaran-Shin (IPS) panel unit root tests, and cointegration relationships were analyzed using Pedroni and Kao tests. The direction and magnitude of long-run relationships among the variables were estimated by the Fully Modified Ordinary Least Squares (FMOLS) method. FMOLS results indicate that economic growth, internet usage, and labor exert a positive effect on CO2 emissions, whereas mobile subscriptions and capital accumulation have a negative effect on CO2 emissions. Dumitrescu–Hurlin panel causality test results reveal a unidirectional causality running from economic growth to CO2 emissions, while bidirectional causality exists between CO2 emissions and each of internet usage, mobile subscriptions, capital accumulation, and labor. In light of these findings, it is concluded that information and communication technologies and capital accumulation may play an effective role in reducing environmental pollution in the Asian countries studied.

1. Introduction

In today's world, two major developments are redefining the global development landscape: digitalization and economic growth. The digital revolution—characterized by the widespread adoption of information and communication technologies (ICT), artificial intelligence (AI), the Internet of Things (IoT), big data analytics, and smart systems—is profoundly transforming economic activities and social structures. At the same time, economic growth, which has lifted millions out of poverty, is generating sustainability concerns due to its association with environmental degradation. This has prompted researchers and policymakers to explore whether digitalization and economic growth can be aligned to promote sustainable environmental management (Feroz et al. 2021; Karlilar et al. 2023).

Digitalization is widely recognized as a mechanism that fosters growth, particularly in the knowledge economy. Bocean and Vărzaru (2023) point out that European countries are beginning to understand the importance of digital transformation in achieving economic and sustainable growth. The World Bank and The Organisation for Economic Co-operation and Development (OECD) emphasize that digital infrastructure and ICT development contribute positively to productivity, gross domestic product (GDP) per capita, and labor market dynamism. Niranga et al. (2022), using panel data from 59 countries, report that digitalization has a positive impact on GDP growth in most regions of the world, with exceptions in parts of North Africa and West Asia. Their analysis covering the period from 2018 to 2020 shows that digital technology development significantly contributes to economic progress in both high-income and upper-middle-income countries. Gao et al. (2023) demonstrate that digital investments facilitate firms' transition to smart manufacturing, reduce inefficiencies, and promote green innovation. Similarly, Wei et al. (2024) examined the impacts of international digital trade, green technology innovation, and renewable energy consumption on the ecological footprint (a measurement that includes carbon emissions as well as some other gases) in the BRICST countries (Brazil, Russia, India, China, South Africa, and Türkiye) using data from 1995 to 2022 using The Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model. They concluded that international digital trade supports a sustainable environment by reducing the ecological footprint, but the accompanying economic growth will harm the environment, and investments in green technology and renewable energy should be encouraged to reduce this. By integrating real-time data and automation, firms can optimize resource allocation, reduce energy consumption, and enhance operational scalability. These improvements ultimately contribute to higher economic output and long-term competitiveness. However, the digital divide—both between and within countries—continues to limit inclusive growth. Infrastructure inequalities, regulatory uncertainty, and digital illiteracy hinder the full potential of digital economies.

The role of digitalization in environmental management and sustainability is thus seen as crucial yet complex. On one hand, digital tools enable precision agriculture, smart grids, digital twin simulations, and AI-based pollution monitoring. For example, Chowdhury et al. (2024) highlight that AI-based applications in the United States help reduce dependence on fossil fuels by optimizing energy use in both residential and industrial sectors. Moreover, integrating foreign direct investment (FDI) with AI-driven energy policies significantly contributes to the green economy. On the other hand, digital tools they create risks associated with energy demand, material extraction, and electronic waste generation. For example, rebound effects, such as rising electricity consumption in data centers and increasing e-waste, pose environmental challenges (Hilty et al. 2006).

Digitalization influences environmental sustainability through four main pathways. First, green innovation, whereby digital infrastructure facilitates investments in cleaner technologies and green patents by both firms and governments. Gao et al. (2023) underline the strong association between digital development, green R&D intensity, and environmental certifications. Second, energy efficiency, with smart systems such as IoT sensors and machine learning algorithms improving energy usage efficiency across multiple sectors. In manufacturing, predictive maintenance and digital twins help reduce energy waste and machine downtime (Feroz et al. 2021). Third, environmental governance, where digital public administration, e-government platforms, and blockchain technologies enhance regulatory transparency and citizen participation. Guan et al. (2024) show that digital governance positively influences natural resource management, particularly in developing economies. Finally, carbon monitoring, through satellite imagery, blockchain for supply chains, and remote sensing tools, improves carbon footprint tracking and reporting, thus facilitating compliance with global climate targets.

This study investigates the relationship between digitalization, economic growth, and environmental sustainability in a sample of 15 developing Asian countries. The motivation for selecting Asian economies lies in their recent robust economic growth—particularly in countries such as China, India, and Türkiye—their large populations representing a significant share of the world's total, and the considerable progress and implementation of digitalization initiatives across multiple sectors in the region.

There are not many studies that address digital transformation and economic growth together in the field of sustainable environmental management. While some studies only address the environmental impacts of digitalization (Majeed 2018; Feroz et al. 2021; Truong 2022; Ebaidalla and Abusin 2022; Ren et al. 2022; Liu and Wan 2023; Ben Jebli et al. 2024), a few studies focused on the relationship between digitalization (ICT, technological innovation), economic growth, renewable energy, globalization and trade openness, financial inclusion and development and environmental sustainability and environmental quality, and researched a single country or small groups of countries (Lee and Brahmasrene 2014; Raheem et al. 2020; Khanal 2021; Kim 2021; Karlilar et al. 2023; Tsimisaraka et al. 2023; Ullah et al. 2024). To address this knowledge shortage, this study addresses two primary gaps in the literature from the perspective of academic, research, and evaluation practices. First, by providing empirical evidence based on long-term comparative panel analysis in the Asian context, it enhances the potential for regional generalization and overcomes the limitations of single-country or short-term studies. Second, its methodological framework—which differentiates between distinct components of digitalization and employs robust panel econometric techniques (unit-root, cointegration, long-run estimation, and panel causality tests)—responds to prominent gaps concerning measurement heterogeneity and endogeneity. Moreover, the study offers a directly actionable evidence base for policymakers and public administrators. Ministries of environment, transport/telecommunications, and finance, as well as regulatory bodies, can apply the framework presented here to align digitalization and capital policies with environmental objectives.

The study comprises four sections. The first section examines the theoretical relationship between digitalization, economic growth, and environmental sustainability. The second section provides a concise summary of recent studies investigating the link between digitalization and environmental pollution. The third section describes the model, data, and methodology used in the study. The final section reports the empirical findings. The conclusion presents policy recommendations based on these results.

2. Literature review

A country's economic growth is shaped by a wide range of factors, including inflation rate, market size, interest rate, population, labor force, capital accumulation, financial development, FDI, trade openness, and natural resources. In recent years, however, ICT have increasingly been recognized as an additional driving force of economic growth (Kumari and Singh 2024). In this regard, studies such as Odhiambo (2022), Yin and Choi (2022), Usman et al. (2021), Solomon and Van Klyton (2020), and Shodiev et al. (2021) have all demonstrated that digitalization exerts a positive effect on economic growth. At the same time, given the rapid development of digitalization in the 21st century, researchers have begun to investigate the potential environmental implications of ICT, particularly its relationship with CO_2 emissions.

This section presents a chronological review of recent studies that explore the relationship between ICT and CO_2 emissions. Lee and Brashmasrene (2014), examining The Association of Southeast Asian Nations (ASEAN) countries for the period 1991-2009 using FMOLS, Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegrating Regression (CCR) methods, find that ICT has a positive impact on both economic growth and CO_2 emissions. Moreover, a bidirectional causality between economic growth and CO_2 emissions is reported. Zhang and Liu (2015), focusing on China, analyze the ICT–CO_2 emissions relationship at both national and regional levels for the period 2000-2010 using panel data methods. Their results reveal that the ICT industry has a negative impact on CO_2 emissions at the national level, with the reduction effect being stronger in central regions than in eastern regions, and weakest in western regions.

Asongu (2018) investigates the interaction between ICT and globalization (trade and financial openness) in 44 sub-Saharan African countries during 2000-2012, employing the The Generalized Method of Moments (GMM) method. The findings suggest that ICT use can mitigate the environmental harm of globalization, particularly through internet and mobile phone penetration, which emerge as policy tools for environmental sustainability. Majed (2018), in a comparative study covering 48 developed and 84 developing countries for 1980-2016, shows that ICT reduces CO_2 emissions in developed countries (supporting the "green ICT" hypothesis) but has negative environmental effects in developing countries. Furthermore, the Environmental Kuznets Curve hypothesis holds for developed nations but not for developing ones, where ICT-driven e-waste management challenges are prevalent.

Raheem et al. (2020), using data from G7 countries (1990-2014) and Pooled Mean Group (PMG) estimators, find that ICT increases emissions in the long run; however, its interaction with financial development mitigates this adverse effect. In the economic growth model, ICT and financial development individually have weak effects, but their interaction yields positive short-term and negative long-term outcomes. Chatti (2021), analyzing 43 countries for 2002-2014 with a two-step system GMM approach, shows that while ICT alone may harm the environment, its integration with transportation sectors (road, rail, air) can reduce CO_2 emissions, especially through fixed-line and mobile technologies combined with rail and inland transportation.

For Australia, Khanal (2021) applies The Autoregressive Distributed Lag (ARDL) bounds testing approach to 1990-2019 data and finds that internet use, energy consumption, and population increase environmental pollution in the short run, while in the long run, internet use and population have a mitigating effect. However, economic growth continues to exacerbate pollution over the long term. Kim (2021), focusing on Korea (1990-2016), finds that economic growth positively affects CO_2 emissions in the long run, while trade openness, financial development, and ICT show no significant long-term effects.

Usman et al. (2021), analyzing nine Asian countries (1990-2018) via the ARDL bounds test, report that ICT use increases CO_2 emissions in Saudi Arabia, Malaysia, Türkiye, Japan, Vietnam, and India in the long run. Batool et al. (2022), studying East and South Asian countries (1985-2020) with the PMG estimator, find that ICT and financial development positively influence CO_2 emissions in the long run but have no significant short-run effects. Granger causality tests indicate one-way causality from ICT and financial development to CO_2 emissions.

Ebeidalla and Abusin (2022) examine Gulf Cooperation Council (GCC) countries using Mean Group (MG) and Augmented Mean Group (AMG) estimators and conclude that ICT raises CO_2 emissions. Liu and Wan (2023), investigating 285 Chinese prefecture-level cities (2004-2018), find a positive relationship between ICT and CO_2 emissions, with energy consumption playing a key mediating role. Tsimisaraka et al. (2023), analyzing the top 10 emitters in the "Belt and Road" (OBOR) region, conclude that ICT infrastructure development can help reduce emissions in both the short and long term.

Ben Jebli et al. (2024), applying the PMG–ARDL approach to 84 countries (2009-2020), find that ICT and renewable energy consumption reduce CO_2 emissions, while financial development, economic growth, and non-renewable energy consumption increase them. Uddin et al. (2024), focusing on G20 countries (1980-2019) using panel ARDL and GMM, show that military expenditure, energy use, and ICT all significantly raise CO_2 emissions. You et al. (2024) examine 64 countries (2000-2021) and find that ICT, human capital, and renewable energy reduce CO_2 emissions. Granger causality tests indicate a bidirectional relationship between ICT and CO_2 emissions.

Finally, Yu and Du (2025) study 11 The Regional Comprehensive Economic Partnership (RCEP) countries using the Panel Smooth Transition Regression (PSTR) model and find that trade openness gradually contributes to CO_2 emission reduction as ICT adoption becomes more widespread. This suggests that the environmental benefits of trade liberalization in the region are contingent upon the diffusion of digital technologies.

3. Data, model, and methodology

In this study, we examine the relationship between digitalization, economic growth, capital, labor, and CO_2 emissions for a panel of 15 Asian countries with common data availability—Bahrain, Brunei Darussalam, China, India, Indonesia, Japan, Malaysia, Oman, Pakistan, Saudi Arabia, Singapore, Republic of Korea, Thailand, Türkiye, and Vietnam—over the period 2001-2022. Following the works of Jóźwik et al. (2023), Uddin et al. (2024), Ben Jebli et al. (2024), Ullah et al. (2024), and Yu and Du (2025), the model is constructed using the variables identified in these studies, and is specified as follows:

$$lnCO2_{it} = \beta_0 + \beta_1 lnGDPPC_{it} + \beta_2 lnINT_{it} + \beta_3\, lnMOB_{it} + \beta_4 lnK_{it} + \beta_5 lnL_{it} + \vartheta_t \qquad (1)$$

All variables in the model are expressed in their natural logarithmic form. Environmental quality is represented by $lnCO_2$, denoting per capita carbon dioxide emissions; economic growth is represented by lnGDPPC, denoting per capita gross domestic product; digitalization is represented by lnINT, denoting the number of individuals using the internet, and lnMOB, denoting the number of mobile cellular subscriptions; lnK represents capital accumulation; lnL represents labor; and ϑ_t denotes the error term. Detailed information on the variables is presented in Table 1.

Methodologically, the study will first examine the stationarity of the variables using the panel unit root tests of Levin, Lin, and Chu (2002) and Im, Pesaran, and Shin (2003). If the variables are found to be stationary, the cointegration relationship between the series will be investigated using the Pedroni and Kao cointegration methods. Furthermore, the cointegration coefficients and their direction will be analyzed using the FMOLS method developed by Pedroni (2000). Finally, the causal relationships between the variables will be examined through the Dumitrescu-Hurlin (2012) causality test.

Table 1. Variable definitions

Variables	Symbol	Definition	Unit	Source
CO2 emissions	CO2	Carbon dioxide emissions (total) excluding Land Use, Land-Use Change, and Forestry (LULUCF)	Metrics tons per capita	World Development Indicators (WDI)
GDP Per Capita	GDPPC	GDP per capita	(constant 2015 US$)	WDI
Internet Users	INT	Individuals using the Internet	(% of population)	WDI
Mobile Cellular Subscriptions	MOB	Mobile Cellular Subscriptions	(per 100 people)	WDI
Capital Formation	K	Gross Fixed Capital Formation	(% of GDP)	WDI
Employers	L	Employers, total	(% of total employment)	WDI

4. Empirical findings

This section presents the findings related to the model established to analyze the relationship between CO_2 emissions and economic growth, digitalization, capital, and labor in Asian countries. Before evaluating the analysis results, the descriptive statistics for the dependent and independent variables in the model are presented in Table 2.

Table 2. Descriptive statistics of the variables

Variables	CO2	GDPPC	INT	MOB	K	L
Mean	5.495	9.143	3.478	4.307	3.266	0.919
Median	5.583	9.303	3.881	4.615	3.279	1.021
Maximum	9.443	11.126	4.605	5.358	3.795	1.992
Minimum	1.715	6.657	-0.415	-0.762	2.551	-1.178
Std. Error	1.706	1.207	1.088	0.987	0.256	0.607
Skewness	0.025	-0.383	-1.087	-2.527	-0.595	-0.489
Kurtosis	2.988	1.838	3.399	10.255	3.627	2.857
Number of Observations	330	330	330	330	330	330

An examination of the descriptive statistics in Table 2 reveals that the maximum logarithmic value for the CO_2 emissions variable, 9.443, was recorded in China in 2021, corresponding to 21.538 MT CO_2e. The minimum logarithmic value of 1.715 was observed in Brunei Darussalam in 1997, corresponding to 44.219 MT CO_2e. For the GDPPC variable, the maximum logarithmic value of 11.216 was observed in Singapore in 2022, equivalent to USD 67,948, while the minimum logarithmic value of 6.657 was recorded in India in 2001, equivalent to USD 778.07. Among the digitalization indicators, the highest logarithmic value for the INT variable (4.605) was observed in Saudi Arabia in 2022, for the MOB variable (5.358) in Bahrain in 2016.

In panel data analyses, it is essential for the series to be stationary to obtain reliable results. Accordingly, to establish a meaningful relationship between the dependent and independent variables and to ensure accurate results, the stationarity of the series must be tested. In studies employing panel data analysis, the Levin, Lin, and Chu (2002) and Im, Pesaran, and Shin (2003) panel unit root tests are frequently used. The results of these tests are presented in Table 3.

An examination of the unit root test results shows that, except for the GDPPC variable, all variables are non-stationary at their levels. However, since the model requires all variables to be stationary, unit root tests were applied after taking the first differences of all variables. Following differencing, both the LLC and IPS unit root test results indicate that all variables have become stationary.

Table 3. Results of panel unit root tests

Level	LLC		IPS	
	Constant and Trend			
	t-statistic	Probability	t-statistic	Probability
CO2	-1.028	0.151	0.617	0.731
GDPPC	-2.231**	0.010	-1.783**	0.037
INT	5.741	1.000	6.560	1.000
MOB	8.805	1.000	13.837	1.000
K	0.610	0.729	0.9111	0.819
L	-0.025	0.489	1.866	0.969
First Differences				
ΔCO2	-10.700***	0.000	-8.743***	0.000
ΔGDPPC	-11.429***	0.000	-9.534***	0.000
ΔINT	-3.855***	0.000	-5.947***	0.000
ΔMOB	-3.500***	0.000	-3.750***	0.000
ΔK	-4.548***	0.000	-4.130***	0.000
ΔL	-3.340***	0.000	-5.549***	0.000

Note: Δ indicates first differences. ***1%, **5%, *10% significance levels.

After confirming the stationarity of the series, the cointegration relationship was examined using the Pedroni and Kao cointegration tests. As shown in Table 4, the Pedroni test results reveal that, in two of the four panel statistics, the null hypothesis is rejected, indicating the existence of a cointegration relationship. Similarly, in the three group statistics of the Pedroni test, the null hypothesis is rejected in two cases, consistent with the panel test results. The Kao cointegration test results, applied to validate these findings, also align with the Pedroni test results.

Table 4. Results of panel cointegration tests

Pedroni Panel Cointegration Test	Without Trend		Weighted	
	t-statistic	Probability	t-statistic	Probability
Panel v-statistic	-1.149	0.874	-1.984	0.976
Panel rho-statistic	2.021	0.978	2.312	0.989
Panel PP-statistic	-2.641***	0.004	-1.745**	0.040
Panel ADF-statistic	-4.014***	0.000	-3.336***	0.000
Group rho-statistic	4.008	1.000		
Group PP-statistic	-1.435*	0.075		
Group ADF-statistic	-3.298***	0.000		
Kao Panel Cointegration Test	**t-statistic**		**Probability**	
ADF	-2.823***		0.0002	

Note: ***1%, **5%, *10% significance levels.

The cointegration coefficient and direction obtained from the Pedroni and Kao cointegration tests were analyzed using the FMOLS estimator, and the results are presented in Table 5.

Table 5. FMOLS coefficient estimator results

Model	$lnCO2_{it} = \beta_0 + \beta_1 lnGDPPC_{it} + \beta_2 lnINT_{it} + \beta_3\, lnMOB_{it} + \beta_4 lnK_{it} + \beta_5 lnL_{it} + \vartheta_t$									
Variable	lnGDPPC		lnINT		lnMOB		lnK		lnL	
Panel	Coef.	p	Coef.	p	Coef.	p	Coef.	p	Coef.	p
	0.202	0.000	0.227	0.000	-0.001	0.085	-0.038	0.069	0.017	0.032

The results of the FMOLS analysis reveal a nuanced relationship between digitalization, economic activity, and environmental outcomes in the context of Asian economies. Specifically, the findings indicate that economic growth, internet usage, and labor force expansion are positively associated with CO_2 emissions. This suggests that while these factors may stimulate productivity, innovation, and overall economic performance, they also contribute to increased energy consumption and a greater reliance on carbon-intensive production and consumption patterns. In particular, internet usage—often considered a driver of efficiency and connectivity—can have unintended environmental costs when supported by energy systems that remain heavily dependent on fossil fuels. Similarly, the expansion of the labor force may lead to higher production volumes and consumption levels, thereby intensifying environmental pressures if not accompanied by shifts toward greener technologies and sustainable practices.

On the other hand, the analysis finds that mobile subscriptions and capital accumulation exert a negative, mitigating effect on CO_2 emissions. This inverse relationship highlights the potential of mobile technologies to contribute to environmental sustainability when leveraged effectively. Mobile applications can facilitate energy management, optimize transportation systems, and enable remote work, all of which can reduce carbon footprints. Capital accumulation plays a similar role by enhancing the capacity to invest in cleaner production methods, renewable energy infrastructure, and advanced technologies that improve resource efficiency. These results underscore the importance of channeling financial resources toward projects and innovations that align with low-carbon development pathways.

When placed in the context of existing literature, these findings demonstrate strong consistency with prior studies, including those by Lee and Brashmasrene (2014), Majed (2018), Raheem et al. (2020), Chatti (2021), Khanal (2021), Kim (2021), and Usman et al. (2021). These works have similarly identified that economic growth and certain dimensions of ICT expansion can have environmentally detrimental effects if not managed within a sustainable framework, while targeted technological adoption and investment can counteract such negative trends. This alignment with previous research reinforces the credibility of the present study's results and provides further empirical evidence for the critical role of strategic ICT deployment and capital investment in balancing the dual objectives of economic progress and environmental protection.

Following the examination of long-run cointegration relationships among the variables at both panel and country levels, the causal relationships between them were analyzed using the Dumitrescu-Hurlin (2012) panel causality test.

Table 6. Dumitrescu-Hurlin granger causality test results

Null (H0) Hypothesis	Wald statistic	Z-bar statistic	Probability
$\ln GDPPC \nrightarrow \ln CO2$	7.109***	3.627	0.000
$\ln CO2 \nrightarrow \ln GDPPC$	4.508	0.938	0.347
$\ln INT \nrightarrow \ln CO2$	8.040***	4.589	0.000
$\ln CO2 \nrightarrow \ln INT$	6.192***	2.680	0.000
$\ln MOB \nrightarrow \ln CO2$	7.709***	4.247	0.000
$\ln CO2 \nrightarrow \ln MOB$	9.331***	5.923	0.000
$\ln L \nrightarrow \ln CO2$	7.700***	4.238	0.000
$\ln CO2 \nrightarrow \ln L$	6.011**	2.492	0.012
$\ln K \nrightarrow \ln CO2$	7.847***	4.390	0.000
$\ln CO2 \nrightarrow \ln K$	7.058***	3.574	0.004

Note: ***1%, **5%, *10% significance levels.

When Table 6, which presents the results of the Dumitrescu-Hurlin (2012) causality test, is examined, it becomes evident that there is a unidirectional causality running from economic growth to CO_2 emissions. This finding implies that changes in economic growth significantly influence the level of CO_2 emissions, whereas variations in CO_2 emissions do not appear to have a statistically significant effect on economic growth in the studied sample. In practical terms, this relationship suggests that as economies expand—through industrialization, higher production levels, and increased consumption—the associated energy demands and reliance on fossil fuels tend to rise, thereby leading to greater carbon emissions. Such a dynamic underscores the environmental costs of growth when it is not accompanied by measures aimed at decarbonization or the promotion of green technologies.

The other key findings indicate the presence of a statistically significant bidirectional causality between internet usage, mobile subscriptions, labor force expansion, and capital accumulation on the one hand, and CO_2 emissions on the other. This mutual relationship highlights that not only do these factors influence environmental outcomes, but changes in environmental quality—particularly rising or falling CO_2 emissions—can also feed back into the level and nature of technological adoption, labor market conditions, and investment patterns. For example, higher internet usage and mobile subscriptions can drive greater energy consumption through data centers, digital infrastructure, and electronic device use, thereby contributing to emissions. At the same time, environmental challenges such as increased carbon emissions can stimulate innovation in energy-efficient ICT solutions, green investment strategies, and changes in labor allocation toward more sustainable sectors.

In the case of labor and capital accumulation, the bidirectional causality reflects a complex interplay between economic resources and environmental pressures. Expanding labor markets and increased capital availability often spur industrial activity, infrastructure projects, and consumer demand, which can elevate CO_2 emissions unless production processes are modernized to reduce carbon intensity. Conversely, heightened environmental degradation and policy responses—such as carbon taxes or incentives for clean energy—can influence how capital is allocated and how labor is deployed, potentially steering both toward greener industries. Overall, the results of Table 6 emphasize the need for integrated policy frameworks that simultaneously address economic development, technological advancement, and environmental protection, ensuring that progress in one domain does not undermine sustainability in another.

5. Conclusion and policy recommendations

Information and Communication Technologies (ICT) have rapidly evolved, making digitalization a key driver of economic growth, production processes, and societal transformation. In the long run, digitalization enhances efficiency by enabling the effective use of resources in production processes, thereby strengthening the foundation for sustainable development. Particularly in areas such as energy efficiency, smart manufacturing systems, and logistics optimization, ICT applications offer significant potential for reducing carbon-intensive activities.

Ren et al. (2022), Wei and Ullah (2022), Yang et al. (2024) have shown that digitalization significantly reduces industrial pollution intensity with an effect that includes green innovation and environmental investment, in other words, digitalization significantly improves environmental quality through improvements in green innovation and reductions in carbon emissions. However, the study’s findings reveal that internet usage and labor exert an increasing effect on CO_2 emissions. This indicates that digitalization does not automatically deliver environmental benefits; on the contrary, when digital infrastructures are energy-intensive and heavily reliant on fossil fuels, they can have adverse environmental impacts.

The results also show that mobile subscriptions and capital accumulation have a reducing effect on CO_2 emissions. Mobile technologies contribute to emission reductions by improving efficiency in areas such as energy management, transport optimization, and environmental monitoring. Capital accumulation, in turn, enhances the capacity to invest in environmentally friendly technologies, facilitating the expansion of renewable energy use and the adoption of cleaner production techniques. In line with these results, Truong (2022) showed that the advancement of digital technologies such as artificial intelligence, big data, the internet of things, and blockchain can help reduce negative impacts on the environment in various ways (waste management and handling, pollution prevention and control, sustainable resource management) and emphasized that digital transformation has tremendous potential in achieving environmental sustainability goals.

In light of these findings, enhancing environmental quality in Asian countries requires the integration of ICT into green transformation strategies. First, to mitigate the environmental impacts of internet usage, the adoption of renewable energy in data centers and telecommunications infrastructure should be prioritized. The environmentally friendly use of mobile technologies should be promoted through the development and widespread deployment of applications that improve energy efficiency and monitor and reduce carbon footprints. Directing capital accumulation toward renewable energy, circular economy practices, and clean production technologies should be supported through tax incentives and low-interest loan programs. Business and political leaders must find digital solutions to produce with less energy. For example, they can reduce energy consumption per product by using smart algorithms, cloud applications, data analytics, data visualization, and Internet of Things (IoT) technologies. They can also reduce carbon emissions by measuring carbon footprints and gaining insight into the environmental impact of products, and they can optimize for sustainability.

Moreover, training programs aimed at equipping the labor force with green skills should be implemented. With these programs, managers will be able to both run their processes efficiently and minimize environmental damage by raising awareness of human resources about green practices. Finally, national-level standards should be established to minimize the energy consumption of digital infrastructures. In this way, energy hunger across the country can be balanced and new fossil fuels, which currently have a very high share of 81% in the world energy supply (IEA 2025), can be avoided.

While digitalization and economic growth may not appear inherently compatible with sustainable environmental management, they can be achieved. This depends on the quality of governance, infrastructure readiness, and policy consistency. From a theoretical perspective, the findings demonstrate that digitalization can have both positive and negative impacts in the context of the economic growth–environment nexus. While ICT can foster environmental improvement when aligned with sustainable energy policies, it can accelerate environmental degradation under unsustainable energy frameworks. Indeed, most leading large ICT companies are not well-positioned in sustainable environmental management, and their consumption of resources (largely energy and rare earth elements, which rely on environmentally harmful fossil fuels) is increasing at a rate comparable to their revenues (D4S 2023). Digital technologies must be used frugal to control the environmental footprint of ICT. Practically, policymakers should design digitalization investments taking into account the structure of energy resources, develop energy efficiency standards, promote sustainable digitalization and develop "green digitalization" strategies that explicitly address environmental objectives while supporting a circular economy. The business models of large ICT companies need to be fundamentally transformed to align with the sustainability transformation. Governments and companies should consider working with initiatives such as CODES (Digital Transformation for Sustainable Development), D4S (Digitalization for Sustainability), and even the United Nations to embrace sustainability goals and reduce the negative environmental impacts of their operations. Truong (2022) argues that digitalization poses serious challenges that must be addressed in the coming years: (a) ICT causes several negative environmental impacts (extraction of mineral resources for production, resource degradation, soil and water pollution, and biodiversity degradation). (b) The volume of e-waste is accumulating annually and is becoming an increasing threat to the environment. (c) Digital transformation requires a large amount of physical hardware. All these physical products require resources and energy throughout their life cycles. Therefore, it is recommended to reduce e-waste flows and reduce the environmental burden by implementing effective sustainable environmental management and improving and expanding recycling.

The main limitations of this study are the restriction of the sample to only 15 Asian countries and the time frame of 2001-2022. Moreover, the use of internet usage and mobile subscriptions as the sole indicators of digitalization excludes other critical ICT components such as AI, IoT, and 5G technology. Future studies could expand the scope to include a larger set of countries and a longer time horizon, as well as examine the environmental effects of different ICT components in more detail. Additionally, incorporating variables such as renewable energy use, energy efficiency indicators, and e-waste management could lead to more comprehensive and robust conclusions.

Declaration of competing interest

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

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Renewable energy, fossil fuels, and globalization: Policy lessons from Japan for a sustainable future

Sevgi SÜMERLİ SARIGÜL[1], Murat ÇETİN[2]

H I G H L I G H T S

[1] Kayseri University, Social Sciences Vocational School, Kayseri, Türkiye, ssumerli@kayseri.edu.tr
[2] Tekirdağ Namık Kemal University, Faculty of Economics and Administrative Sciences, Tekirdağ, Türkiye, mcetin@nku.edu.tr

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The direct use of the load capacity factor to measure environmental quality has opened up a new area in the analysis of environmental quality determinants. In this context, this study identifies renewable energy, non-renewable energy, and globalization as explanatory variables for the load capacity factor in the Japanese economy. Using annual data from 1990 to 2021, this study applies the ARDL bounds test, FMOLS, and DOLS estimators. The results indicate that the series are stationary in differences and that a long-term relationship exists between the variables. The FMOLS and DOLS estimates confirm that the use of renewable energy increases the load capacity factor, while the use of non-renewable energy and globalization decreases it. Thus, renewable energy usage improves environmental quality, whereas non-renewable energy usage and globalization worsen it. The empirical findings emphasize the need to support the renewable energy sector to improve environmental quality, while also highlighting the necessity to reconsider the strategies related to globalization and the non-renewable energy sector.

1. Introduction

The environment has complex dynamics with the socio-cultural structure. The growing concerns over environmental degradation and climate change have led to a greater emphasis on the energy consumption-environmental outcomes link. Energy production, particularly from non-renewable sources, has been identified as a major contributor to environmental pollution, while renewable energy sources are often seen as a solution to mitigating these adverse effects. In this context, this study examines how the use of energy sources affects environmental quality in the context of the Japanese economy. This study focuses on the following research questions for the Japanese economy:

- Can the use of renewable energy improve environmental quality?
- What is the relationship between globalization and environmental quality?
- Does the consumption of non-renewable energy deteriorate environmental quality?

The study is very important for literature. First, it is a rare study that investigates the relationship between variables, including not only renewable and non-renewable energy usage but also globalization, within the environmental quality model in the specific context of Japan. Second, the study analyzes the country's data from the 1990-2021 period using time series techniques. Third, while the ARDL bounds test is employed for the cointegration analysis of the series, FMOLS and DOLS estimators are used for coefficient estimation. The results obtained could provide valuable recommendations to policymakers in Japan, helping them make informed decisions regarding energy strategies and environmental policies.

Furthermore, the study also explores the potential long-term and short-term effects of energy consumption patterns on environmental quality, offering insights into how shifts between renewable and non-renewable energy sources could impact Japan's ecological footprint. By considering the influence of globalization, the research recognizes that external factors such as international trade, technological advancements, and global economic trends may further complicate the relationship between energy use and environmental outcomes. This broader perspective not only strengthens the understanding of Japan's unique position but also offers a comprehensive framework that could be applied to other nations facing similar challenges in balancing energy consumption with environmental degradation. The study's findings are anticipated to be particularly useful for designing policies that not only address Japan's energy needs but also contribute to achieving global environmental goals.

2. Literature review

2.1. Theoretical backround

Both human and industrial activities require intensive energy consumption, and this demand is met through various energy sources. These sources are generally classified into three categories: nuclear, renewable, and non-renewable energy. In addition to traditional factors of production such as labor, capital, and entrepreneurship, economists working in the field of energy economics consider energy consumption as a fundamental production input and view it as a driving force behind economic development (Abbasi et al. 2021).

One of the most important factors influencing individual well-being is environmental quality. Reducing the use of fossil fuels can be extremely challenging for many national economies, as fossil fuels remain one of the main drivers of economic growth. However, the transition to clean energy sources poses significant challenges. There is a broad consensus that the increase in CO_2 emissions resulting from industrial development is directly linked to the use of non-renewable energy sources (Mendoza-Rivera et al. 2023).

The persistent dependence of societies on energy is a root cause of many environmental problems. Therefore, to address these environmental challenges and reduce the emissions of highly polluting gases such as CO_2, the use of clean technologies and energy sources has become a fundamental necessity for both developed and developing countries. A large body of literature suggests minimizing reliance on non-renewable energy by promoting the use of alternative, renewable energy sources (Xie and Jamaani 2022; Ding et al. 2021; Hao et al. 2021). The use of green and renewable energy sources can make significant contributions to the future of the environment. These alternative energy options are vital for achieving sustainable development (Amin et al. 2023).

Another variable that can impact environmental sustainability is globalization. Globalization may affect environmental quality in both positive and negative ways. The relationship between globalization and the environment is explained through three mechanisms: the scale effect, the technique effect, and the composition effect. On one hand, globalization increases economic activities such as transportation, production, and consumption, which may lead to environmental degradation. On the other hand, it offers important opportunities for the transfer and development of energy-efficient technologies, thereby potentially improving environmental quality and mitigating environmental harm (Awad and Mallek 2023).

2.2. Empirical literature

Mesagan and Nwachukwu (2018) examine the financial development-environmental quality link for Nigeria. Their long-term ARDL estimates confirm the validity of the EKC hypothesis, showing that financial development, energy consumption, and technological innovation contribute to environmental degradation through increased CO2 emissions.

Similarly, Zafar et al. (2020) explore the influence of FDI and education on environmental pollution in Asian economies. Using FMOLS and DOLS approaches, they find that both factors worsen environmental quality by boosting CO2 emissions. They also identify a positive link between independent variables and CO_2 emissions, suggesting that these factors exacerbate environmental degradation.

Zafar et al. (2022) focus on the link among ICT, education, and environmental degradation in Asia. Their analysis, using second-generation panel estimators like CUP-FM and CUP-BC, reveals that economic growth, energy consumption, and education promote CO2 emissions. Conversely, ICT and financial development are associated with a reduction in CO2 emissions, indicating that these factors may help mitigate environmental degradation.

Zhang et al. (2022) investigate the institutional factors-environmental quality link through the NARDL technique. Their results show that positive shocks in institutional factors negatively affect CO2 emissions, while negative shocks have a detrimental effect, increasing CO2 emissions.

Yapraklı et al. (2023) apply panel data analysis to explore the drivers of environmental degradation in the Turkic Republics and Turkey. Their findings, based on the panel AMG estimator, reveal that non-renewable energy consumption exacerbates the ecological footprint, while renewable energy consumption helps reduce it. They also show that economic growth drives environmental degradation, while the economic complexity index plays a role in mitigating it.

Bajja et al. (2023) investigate Morocco. Their estimates indicate that energy consumption, FDI, and urbanization accelerate CO_2 emissions, contributing to environmental degradation. Interestingly, while economic growth and financial development were found to have a negative effect, these relationships were not statistically significant. Granger causality tests reveal a causality from energy consumption and financial development to CO_2 emissions.

Abbasi et al. (2021) tested the relationship between renewable energy and CO_2 emissions for the Thai economy using the dynamic ARDL approach. Their findings indicate that renewable energy and economic growth have a mitigating effect on CO_2 emissions in both the short and long run.

Focusing on the relationship between green growth and CO_2 emissions in the context of G7 countries, Hao et al. (2021) included economic growth, renewable energy, and environmental taxes as independent variables in their pollution model. The CS-ARDL model results confirm the validity of the Environmental Kuznets Curve (EKC) hypothesis and find that human capital, environmental taxes, energy intensity, and the use of renewable energy contribute to environmental improvement by reducing CO_2 emissions.

Using panel data approaches, Ding et al. (2021) investigated the drivers of CO_2 emissions in G7 economies. The CS-ARDL outputs show that imports and economic growth contribute to higher CO_2 emissions, whereas green innovations, exports, and the use of renewable energy help reduce emissions. Additionally, their findings reveal unidirectional causality running from exports, imports, economic growth, green innovations, and renewable energy to CO_2 emissions.

Xie and Jamaani (2022) examined the relationship between green innovations, energy efficiency, and CO_2 emissions in developed economies and proposed policy recommendations for sustainable development. Their MMQR estimator finds that economic growth drives CO_2 emissions across all quantiles. The results also provide evidence that renewable energy, green innovations, and environmental taxes reduce CO_2 emissions across all quantiles.

Saidi and Omri (2020) investigated the determinants of CO_2 emissions in OECD countries, with a particular focus on the effects of nuclear and renewable energy. FMOLS estimation results reveal that both nuclear and renewable energy consumption contribute to lowering CO_2 emissions.

Doğan and Şeker (2016) analyzed the drivers of CO_2 emissions in the European Union. Using panel data techniques, their study carefully considered the role of renewable and non-renewable energy sources. The results show that renewable energy has a negative effect, while non-renewable energy has a positive effect on CO_2 emissions. Panel causality tests indicate a bidirectional causal relationship between renewable energy and CO_2 emissions, and a unidirectional causality running from CO_2 emissions to non-renewable energy.

Voumik et al. (2023) analyzed static and dynamic panel techniques for G7 countries. The fixed-effects (FE) and random-effects (RE) panel regressions suggest that coal, oil, and natural gas consumption increase CO_2 emissions, whereas the use of renewable and nuclear energy reduces emissions. System GMM estimations produce similar results, reinforcing the previous findings.

Idroes et al. (2024) explored the relationship between the use of renewable and non-renewable energy and both CO_2 emissions and the ecological footprint in Indonesia using time series techniques. FMOLS and DOLS estimations reveal that coal and natural gas consumption, along with economic growth, increase CO_2 emissions, while renewable energy and fixed capital formation help reduce them. These estimations also suggest that oil consumption and economic growth increase the ecological footprint, whereas renewable energy use and fixed capital formation decrease it.

Amer et al. (2024), within the framework of the STIRPAT model, comprehensively examined CO_2 emissions and their key drivers in GCC countries. The results from the GLS estimator show that oil and natural gas consumption, economic growth, population, and final energy use all contribute to increased CO_2 emissions, while renewable energy use helps mitigate them. PCSE and GMM estimators yield results that are highly consistent with those of the GLS, and none of the three estimators found a significant relationship between coal consumption and CO_2 emissions.

Çetin et al. (2025) investigate the relationship between green growth and carbon emissions for the G7 economies. The main finding of the study is that green growth and energy efficiency enhance environmental quality by reducing carbon emissions. On the other hand, Avcı et al. (2024) focus on the impact of tourism and a set of explanatory variables on environmental quality for 15 countries. The results of the study reveal that tourism, renewable energy, and green innovation improve environmental quality.

Finally, Onyeneke et al. (2024) analyze environmental quality in Africa using fixed effects and quantile regression techniques. Their findings suggest that economic growth, livestock production, and FDI are positively correlated with the ecological footprint, while renewable energy usage, crop production, urbanization, and natural resource revenues help reduce the ecological footprint, mitigating environmental degradation.

In addition to the studies mentioned above, recent research has further explored the complex relationship between energy consumption, economic growth, and environmental quality across different regions. These studies highlight the diverse factors influencing environmental degradation and offer valuable insights into the potential solutions for mitigating ecological damage.

3. Econometric model and methodology

The study detects the effects of ICT and financial development on environmental quality in the Japanese economy using the following time series regression model:

$$lnLCF_t = \alpha + \gamma_1 lnNREN_t + \gamma_2 lnREN_t + \gamma_3 lnGLOB_t + \varepsilon_t \quad (1)$$

In this linear regression equation, ε and α represent the error term and the constant term, respectively. γ_1, γ_2 and γ_3 are the elasticity coefficients, which explain the elasticities of non-renewable energy consumption, renewable energy consumption, and globalization, respectively, in relation to the loading capacity factor (environmental quality). This is undoubtedly due to the use of the logarithmic forms of the variables. In this model, LCF is the dependent variable, representing the loading capacity factor. NREN stands for non-renewable energy consumption, REN represents renewable energy consumption, and GLOB refers to the globalization index, the independent variables.

Table 1. Information of Series

Variables	Symbol	Criteria	Source
Loading capacity factor	LCF	Per capita biocapacity/ecological footprint)	GFN
Use of non-renewable energy	NREN	Oil consumption (million tonnes)	BP
Use of renewable energy	REN	Renewable energy use (% of final energy use)	WDI
Globalization	GLOB	Financial globalization index	KOF-SEI

The series consists of annual data from the period 1990-2021, sourced from the GFN, WDI, and KOFSEI databases. All information related to the variables is revealed in Table 1. A graphical representation of all the variables used in the study is presented in Figure 1.

Economic methodology can be divided into three parts. In the first part, the stationarity analysis is conducted using unit root tests by Ng-Perron (2001). In the second part, the presence of cointegration is examined using the bounds testing technique by Pesaran et al. (2001). In the final part of the methodology, long-term forecasts are made using the DOLS and FMOLS estimators.

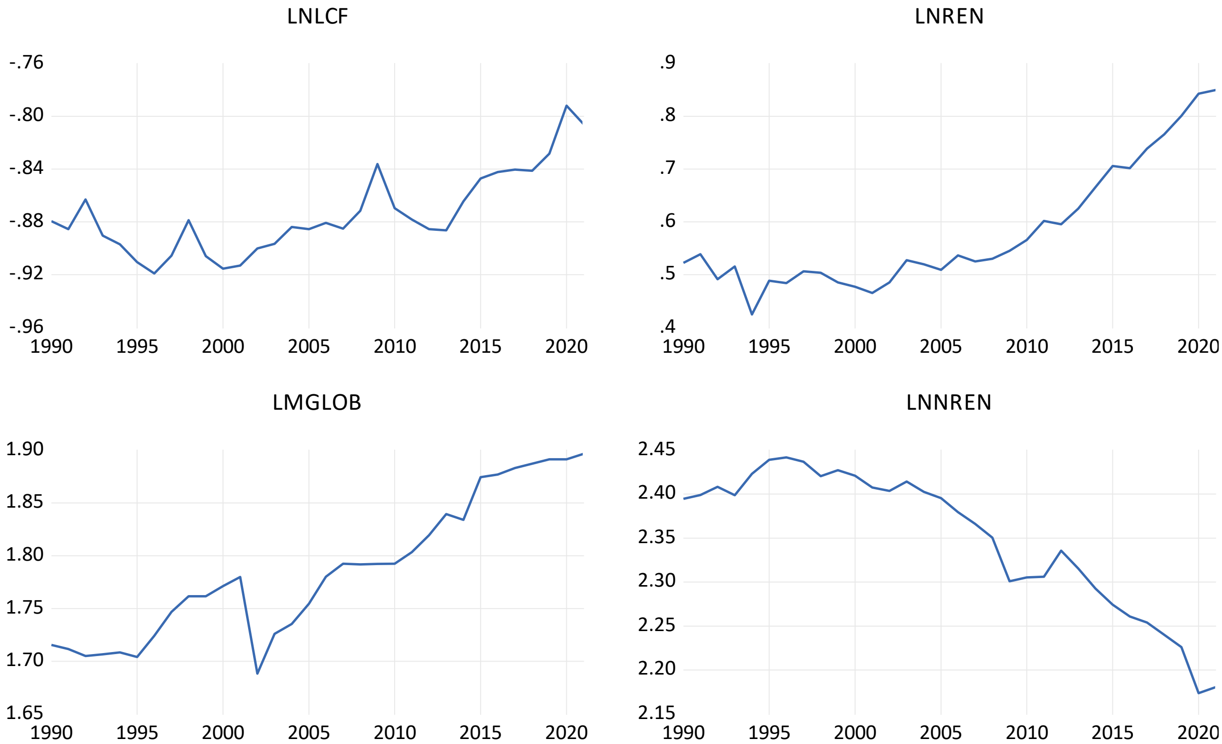

Figure 1. Temporal trends of the variables (1990-2021)

4. Econometric findings

One of the first analyses in empirical studies is the examination of summary statistics. All of these statistics are presented in Table 2. The mean values of lnLCF, lnNREN, lnREN, and lnGLOB are -0.874, 2.349, 0.579, and 1.785, respectively. The variables with the highest and lowest median values are lnLCF and lnNREN. Among the summary statistics with 32 observations, the variable with the lowest and highest minimum and maximum values is lnLCF.

Table 2. Summary statistics

	lnLCF	lnNREN	lnREN	lnGLOB
Average	-0.874	2.349	0.579	1.785
Median	-0.882	2.386	0.528	1.780
Max.	-0.792	2.441	0.849	1.896
Min.	-0.919	2.173	0.424	1.688
Standard deviation	0.031	0.078	0.116	0.066
Skew	0.848	-0.731	1.055	0.336
Kurtosis	3.195	2.368	2.919	1.861
Observation	32	32	32	32

After the summary statistics, the unit root analysis is conducted. The outcomes are presented in Table 3. The Ng-Perron test findings indicate that each variable contains a unit root at the level in all four statistics, namely MZa, MZt, MSB, and MPT, but becomes stationary after taking the first difference

Table 3. Unit root results

Panel A.		**Level**		
Variables	**MZa**	**MZt**	**MSB**	**MPT**
lnLCF	-2.571	-0.807	0.314	8.175
lnNREN	1.826	1.312	0.718	44.892
lnREN	1.883	1.153	0.612	34.753
lnGLOB	0.081	0.042	0.523	20.491
Panel B.		**First Difference**		
Variables	**MZa**	**MZt**	**MSB**	**MPT**
lnLCF	-14.949***	-2.709***	0.181***	1.729***
lnNREN	-14.515***	-2.681***	0.184***	1.735***
lnREN	-14.098***	-2.653***	0.188***	1.743***
lnGLOB	-14.454***	-2.687***	0.185***	1.697***

The unit root results also bring up the question of whether there is cointegration among the variables. To address this, the ARDL bounds test is employed. The empirical results obtained are presented in Table 4. The appropriate model for ARDL is the one with a lag length of 1,1,1,0. Since the calculated F-statistic value of 6.506 is higher than the critical upper bound of 4.92, we can conclude that there is cointegration among the variables, namely lnNREN, lnREN, lnGLOB, and lnLCF, at the 1% significance level. This also indicates a long-term relationship.

Table 4. ARDL results

Optimal latency	[1,1,1,0]	
F- Statistics	6.506***	
Critical values		
Significance level	***Lower limit, I*(0)**	***Upper limit, I*(1)**
1%	3.81	4.92
5%	2.79	3.67
10%	2.37	3.20
Diagnostic tests		
Breusch-Godfrey LM test	2.400 (0.134)	
ARCH LM test	0.184 (0.670)	
J-B normallik test	0.615 (0.735)	
Ramsey RESET test	0.013 (0.907)	
CUSUM	Stable	
CUSUMsq	Stable	
R^2	0.928	
Adj. R^2	0.910	
F- Statistics	52.094***	
Prob.	0.000	

After determining the presence of cointegration, the next step is to determine the long-term coefficients, marking the final stage of the analysis. The FMOLS estimation results in Table 5 show that the coefficient for lnNREN is (-0.416), which is negative and statistically significant. This indicates a negative link between lnNREN and lnLCF, suggesting that non-renewable energy consumption negatively impacts the loading capacity factor, i.e., environmental quality.

The coefficient for lnREN is (0.098), which is positive and significant, indicating a positive relationship between lnREN and lnLCF. From another perspective, this means that the use of renewable energy enhances the loading capacity factor, i.e., environmental quality. This finding is supported by the results of Saidi and Omri (2020) for OECD countries and those of Xie and Jamaani (2022) for developed economies. These studies demonstrate that renewable energy improves environmental quality by reducing CO_2 emissions.

Lastly, since the coefficient for lnGLOB is (-0.242), which is negative and significant, it suggests a negative link between lnGLOB and lnLCF. This provides important evidence that globalization reduces the loading capacity factor, and therefore environmental quality.

When comparing FMOLS estimates to DOLS estimates, overlapping findings can be observed. Just as in the FMOLS estimates, the DOLS estimates show that lnNREN and lnGLOB have negative effects, while lnREN is positive. Thus, the first two variables improve environmental quality, whereas the third variable worsens it.

Table 5. Long-term forecasts

Panel A.		**FMOLS Results**	
Variables	**Coefficients**	**Standard error**	**Prob.**
lnNREN	-0.416***	0.076	0.000
lnREN	0.098*	0.048	0.052
lnGLOB	-0.242**	0.065	0.000
Panel B.		**DOLS Results**	
Variables	**Coefficients**	**Standard error**	**Prob.**
lnNREN	-0.343***	0.082	0.000
lnREN	0.221***	0.053	0.000
lnGLOB	-0.394***	0.090	0.000

5. Conclusion and recommendations

This study is designed to investigate how renewable energy, non-renewable energy, and globalization affect the loading capacity factor, and thus environmental quality, with a focus on the Japanese economy. In this study, covering the period from 1990 to 2021, the ARDL bounds test as well as the FMOLS and DOLS estimators were utilized.

The findings indicate that the series have not unit root at their first differences, and the presence of cointegration has been confirmed. The study shows that while renewable energy usage improves environmental quality, globalization and non-renewable energy usage have a detrimental effect on environmental quality.

The finding that renewable energy use improves environmental quality is consistent with the results of Omri (2020) and Xie and Jamaani (2022). On the other hand, the finding that globalization deteriorates environmental quality supports the outcomes reported by Awad and Mallek (2023) for African countries.

These findings could provide valuable insights for policymakers. The discovery that renewable energy usage positively impacts environmental quality suggests that policies accelerating investments in the renewable energy sector in the Japanese economy should be implemented, thus preventing environmental degradation. The negative effects of non-renewable energy usage and globalization on environmental quality highlight the need to reconsider fossil fuel use and globalization practices.

Furthermore, the results underscore the importance of adopting a balanced energy mix, where renewable energy sources play a key role in reducing environmental degradation. Policymakers should consider enhancing incentives for renewable energy technologies and infrastructure while gradually transitioning away from heavy reliance on non-renewable energy sources. The financial sector should prioritize and support projects and investments related to the renewable energy sector. In addition, globalization's impact on environmental quality should be carefully managed through international cooperation, sustainable trade policies, and environmental standards that promote greener practices across borders. By aligning energy policies with environmental sustainability goals, Japan can not only improve its environmental quality but also set an example for other nations in the transition to a sustainable energy future.

This study, which investigates the drivers of environmental quality for Japan, has certain limitations. While examining the effects of non-renewable energy, renewable energy consumption, and globalization on CO_2 emissions, it does not include other potential determinants of environmental quality such as green technological innovations, green growth, and trade openness in the model. Moreover, the study does not incorporate recent time series techniques such as dynamic ARDL, Fourier ARDL, or bootstrap ARDL. Future research is recommended to consider these additional variables and advanced modeling approaches.

Declaration of competing interest

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

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Evaluation of return performance of sustainability themed mutual funds with NMD and WASPAS method

Arif ÇİLEK[1], Onur ŞEYRANLIOĞLU[2], Elif ÇİLEK[3]

HIGHLIGHTS

[1] Giresun University, Bulancak Kadir Karabaş School of Applied Sciences, Giresun, Türkiye, arif.cilek@giresun.edu.tr
[2] Giresun University, Faculty of Economics and Administrative Sciences, Giresun, Türkiye, onurseyranlioglu@gmail.com
[3] Giresun University, Institute of Social Sciences, Giresun, Türkiye, elifcilek2861@gmail.com

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ABSTRACT

The aim of this study is to examine the performance of sustainability-themed funds by comparing three fund categories: variable umbrella funds, fund-of-funds umbrella funds, and equity umbrella funds. The dataset comprises May 2022-April 2025 data for 16 sustainability-themed umbrella funds traded on TEFAS, each with at least three years of historical returns. These 16 funds were divided into three groups according to their fund type. The selection criteria included monthly, three month, six month, year to date, 12 month, and 36 month return percentages, as well as changes in portfolio size and share count. Criterion weights were determined using the Normalized Maximum Difference (NMD) method, and performance rankings were produced using the WASPAS (Weighted Aggregated Sum Product Assessment) method. Sensitivity analyses were conducted to observe how WASPAS rankings change under different parameter settings. According to the NMD results, change in portfolio size emerged as the most influential criterion, while the six month return carried the least weight. The WASPAS ranking placed the TMC variable umbrella fund first, followed by the GZV fund-of-funds umbrella fund and the IHK equity umbrella fund. TMC's top scores across all criteria support its identification as the best alternative among the sustainability-themed funds. The lowest rankings were assigned to the YJH variable umbrella fund, the IFN equity umbrella fund, and the AOY equity umbrella fund, respectively.

1. Introduction

Mutual funds are investment vehicles that pool capital from savers to construct a portfolio of various assets, such as equities, bonds, and other securities. Offering professional management and the benefits of diversification, these funds have become an attractive option-especially for individual investors building their savings. When investors purchase shares in a fund, they acquire partial ownership of the underlying assets, and their returns fluctuate according to those assets' performance (Hayes 2025). As mutual funds continue to evolve, changes in regulatory frameworks, technological advancements, and investor behavior are reshaping the interaction between theoretical approaches and practical strategies, ensuring that this topic remains central to discussions in finance and investment management (Gupta et al. 2022; Hayes 2025).

The relationship between mutual funds and financial theories is a significant area of study that influences how individual and institutional investors allocate their resources. Mutual funds—which pool capital from multiple savers to create diversified portfolios—have been a cornerstone of modern investing since their emergence in the 1920s. Their growth is closely tied to the evolution of foundational financial theories such as Modern Portfolio Theory (MPT) and the Efficient Market Hypothesis (EMH), both of which provide frameworks for understanding risk, return, and market behavior in the context of diversified investment strategies. Developed by Harry Markowitz, MPT revolutionized portfolio management by highlighting the importance of diversification in optimizing risk and return. This theory not only shaped mutual fund strategies but also paved the way for the rise of index funds—aligned with EMH principles—and the broader adoption of passive management approaches. EMH asserts that asset prices reflect all available information, thereby challenging the likelihood of consistently achieving above-average returns through active management (Markowitz 1959; Elton et al. 2009; Fischer 2019; Hayes 2025).

As environmental degradation and climate change have gained increasing importance in recent years, sustainability-themed investments have moved to the forefront of investors' attention. International policy-level discussions on climate change have influenced public opinion and demand, and it has become increasingly clear that these issues represent critical areas where the worst effects of the climate crisis are felt. This heightened awareness has significantly boosted demand for thematic investments such as green infrastructure, renewable energy, and water management. Investors now prefer investments that not only offer attractive financial performance but also deliver measurable, transparent, and accountable social and environmental impacts. This trend has led capital markets to more fully internalize sustainability criteria and to restructure financial products in accordance with environmental, social, and governance (ESG) standards (Renneboog et al. 2011; European Commission 2016; Nicholls 2015; CBI 2017; Eurosif 2018). Within this framework, sustainability-themed investment funds are designed to prioritize ESG factors in their investment strategies while aiming to deliver positive financial returns. Reflecting growing societal awareness of sustainable and ethical investing, these funds are supported by evidence that companies with strong ESG practices can outperform their traditional peers. Furthermore, findings suggest that companies incorporating sustainability criteria into their investment decisions tend to perform better than those that do not. Moreover, most studies have found a positive relationship between ESG performance and corporate financial performance (Scholtens 2006; Pisano et al. 2012; Friede et al. 2015; Khan et al. 2016; Kölbel et al. 2017; Gao et al. 2024).

As global awareness of sustainability issues increases, these funds have become increasingly important among investors seeking to combine ethical concerns with financial performance. Evaluating the return performance of sustainability-themed investment funds has become a focal point for the investment community, both in terms of impact and financial returns. As investors demand greater transparency and accountability, fund managers are driven to adopt rigorous evaluation processes that align with their impact objectives and regulatory expectations. This study was conceived on the premise that accurately and meticulously measuring the return performance of sustainability-themed funds in Türkiye can serve as a roadmap for investors. In this context, the main research question of this study is: How are the return performances of sustainability-themed investment funds traded on the Türkiye Electronic Fund Trading Platform evaluated between May 2022 and April 2025 using NMD and WASPAS methods and are there any performance differences between these funds? Its purpose is to analyze the return performance of sustainability-themed funds traded on the Türkiye Electronic Fund Trading Platform over the May 2022-April 2025 period. Sixteen umbrella funds with at least three years of data—five variable, four fund-of-funds, and seven equity umbrellas—were included. The importance weights of various return criteria affecting fund selection were determined, and funds were ranked accordingly. Multi-Criteria Decision-Making (MCDM) methods were chosen for both criterion weighting and performance ranking because they allow investors to evaluate multiple quantitative criteria and make more objective decisions. Criterion weights were calculated using the Normalized Maximum Difference (NMD) method, and fund rankings were produced using the Weighted Aggregated Sum Product Assessment (WASPAS) method.

The remainder of the study is structured as follows. Chapter 2 presents the literature review; Chapter 3 details the methods used; Chapter 4 describes the dataset, implementation process, and findings; and the study concludes with the results and discussion.

2. Literature review

In this literature review, studies examining the performance of international, national, and sustainability-themed investment funds are presented in sequence. In the final stage of the review, several studies that have applied the NMD and WASPAS methods—used in this research—are summarized.

There is a wealth of studies in the international literature that compare the performance of investment funds. For example, Hayat and Kraeussl (2011) examined the return performance of 145 Islamic and conventional equity funds selected from various countries over the 2000-2009 period and found that Islamic funds underperformed their conventional counterparts. Kaushik et al. (2011) evaluated 1.374 actively managed funds between 2000 and 2011, comparing the characteristics of "winning" versus "losing" portfolios; they reported that successful portfolios had lower average expense ratios, lower turnover, and longer manager tenures. Nainggolan et al. (2016) compared the 1984-2010 performance of 496 equity funds from 32 countries and likewise found that Islamic funds delivered weaker returns than their conventional peers. Focusing on the Indonesian market, Agussalim et al. (2017) compared Islamic and conventional equity funds traded between 2007 and 2014, concluding that conventional funds outperformed Islamic ones. In a comparison of actively managed versus passive index funds, Crane and Crotty (2018) showed that passive funds consistently outperformed active managers. Boo et al. (2017), studying Malaysia's three major crisis periods—the 1996 Asian Crisis, the 2000 dot-com bubble, and the 2008 global financial crisis—analyzed fund performance from 1996 to 2013; they observed no significant performance gap between Islamic and conventional funds during the first two crises, but found that Islamic funds proved more resilient during 2008. Mansor et al. (2020) investigated the relationship between security selection and market-timing skills of portfolio managers of Malaysian Islamic equity funds, finding no significant performance difference between Islamic and conventional funds. In a U.S. market analysis covering 1987-2018, Climent et al. (2020) reported that Islamic funds outperformed conventional ones. Jones and Mo (2021) examined the predictive power of past fund performance for future returns and found that the persistence of equity fund alphas has diminished over time. Mirza et al. (2022) compared risk-adjusted performance, investment preferences, and volatility-timing of Islamic versus conventional equity funds during the COVID-19 pandemic, demonstrating that Islamic funds acted as a "safe haven" and showed greater resilience in crisis conditions. Finally, Nanigian (2022) compared active and passive fund performance and reported no statistically significant differences between the two groups.

Numerous studies have compared the performance of investment funds within the Turkish context. Karatepe and Gökgöz (2007) examined the timing and selection skills of A-class mixed equity funds during 2001-2002, finding that these funds generally outperformed the benchmark portfolio except during the 2000-2001 crisis, which disrupted performance persistence. Korkmaz and Uygurtürk (2011) compared equity-weighted pension funds, exchange-traded funds, and A-class equity funds from November 2006 to November 2009, reporting that A-class and pension funds performed similarly and both outperformed ETFs, while market-timing skills of portfolio managers were not statistically significant. Ege et al. (2016) evaluated income-oriented debt pension funds from January 2012 to December 2014 using the M2, Sharpe, Treynor, and Jensen measures, ranking them via the ELECTRE I method; they found Allianz Hayat ve Emeklilik and Aegon Emeklilik leading, whereas Garanti, Vakıf, and Ziraat pension funds lagged. Kıyıcı et al. (2016) compared individual retirement funds in the 2010s using TOPSIS, VIKOR, and MOORA methods, observing similar rankings from TOPSIS and MOORA but differing results with VIKOR. Uysal and Adalı (2018) analyzed equity-weighted Islamic versus conventional pension funds over 2014-2017, concluding that Islamic funds underperformed their conventional peers. Bayraktar and Aksoy (2020) studied Islamic pension funds from 2014 to 2019 in terms of performance, portfolio selection, and timing, finding generally weak performance. Güçlü and Şekkeli (2020) compared performance and managers' market-timing and selection skills of Islamic and conventional equity funds from 2015 to 2020, reporting no significant differences. Uygurtürk and Bal

(2020) evaluated pension and other securities funds from 2015 to 2018 using Sharpe, Treynor, Sortino, and beta measures combined with Grey Relational Analysis (GRA), noting that the two fund types generally performed similarly. Güçlü (2022) applied GRA to three participation and 39 conventional equity umbrella funds traded between 2019 and 2021, highlighting that participation funds offered better risk-return balances and suited investors with Islamic sensitivities. Çömlekçi (2024) classified 55 equity umbrella funds traded on TEFAS from January 2019 to December 2023 into eight strategy-based groups and analyzed them via Entropy and TOPSIS methods; fund management fees and medium-term returns were the most influential selection criteria, sector and participation funds delivered the highest performance, and those focused on BIST 100/30 and affiliated-company shares recorded the lowest. Finally, Akkaya and Ekinci (2024) introduced the Omega ratio for pension fund performance analysis, demonstrating its applicability by showing that debt-instrument funds had the highest and equity funds the lowest Omega values.

Numerous national and international studies have compared socially responsible and sustainability-themed investment funds. Amenc and Le Sourd (2008) analyzed French socially responsible investment (SRI) funds over 2002-2006 using the Fama-French three-factor model and Jensen's alpha. They found negative alpha values and noted that the short data period and young fund ages prevented statistical significance, concluding that the funds offered neither return nor risk advantages during that period. Ibikunle and Steffen (2015) compared 175 European "green" funds to 259 conventional funds from 1991 to 2014. They observed that while green funds underperformed overall, they outperformed conventional peers in 2012-2014 and forecast that green fund performance would improve in the future. Lean et al. (2015) examined 500 European and 248 North American SRI funds over 2001-2011, reporting that both regions' funds generated excess returns over their benchmarks, with European funds exhibiting higher performance and positive persistence. Jin and Han (2017) studied Chinese green funds from 2010 to 2016 via the Fama three-factor model, finding that these funds were highly sensitive to the market factor and exhibited sector-dependent beta values. Ielasi and Rossolini (2019) compared risk-adjusted performance of nearly 1,000 European thematic funds—302 sustainability-themed, 358 other responsible funds, and 341 other thematic funds—over 2007-2017. They concluded that sustainability-themed funds' performance was driven more by their responsible investing framework than by thematic choice, resembling other SRI funds more than thematic ones, and that these funds weathered volatile periods better than other thematic strategies. Marti Ballester (2021) evaluated 111 China-based UN SDG-themed equity funds over 2009-2019 using alpha and factor models, finding returns on par with benchmarks; energy-themed funds underperformed, health-themed funds outperformed, and Chinese and U.S. indices moved in parallel. Yue et al. (2020) assessed 30 European sustainability-themed and 30 conventional funds using annual returns, Fama-French three-factor, and Carhart models, noting that while sustainable funds appeared less risky, there was insufficient evidence of performance differences versus benchmarks and conventional funds, and that increased demand might itself raise risks. Saci et al. (2022) analyzed daily returns of 64 Chinese SRI funds from 2016-2019, finding lower risk but no statistically significant return difference; regression results indicated a positive contribution to Chinese market returns. Ateş et al. (2022) studied Turkish sustainability-themed funds traded from 2019-2022, using daily data against XUSRD and XU100 indices and evaluating annual returns, Sharpe, Jensen's alpha, and Treynor ratios. Under the Capital Asset Pricing Model, they found that SRI funds outperformed conventional peers and market indices in systemic risk-return comparisons. Finally, Satyanegara (2024) compared sustainable and conventional funds in Europe and ASEAN, examining return, risk, and risk-adjusted performance; although sustainable-themed funds grew significantly in number, they did not exhibit statistically significant performance differences compared to conventional funds overall.

When the literature is reviewed, it becomes clear that, despite extensive international research on the performance of sustainability- and socially-responsible funds, in-depth analyses of sustainability-themed funds in Türkiye remain very limited. The lack of empirical data on the performance of these rapidly proliferating funds on TEFAS since 2019 points to a significant gap, both academically and practically. Moreover, it is crucial that such performance analyses be conducted using rational, systematic methods. As shown in Table 1, multi-criteria decision-making methods like NMD and WASPAS have been widely explored in the literature, yet they have scarcely been applied to fund-return performance analyses. For all these reasons, this study makes a valuable contribution by addressing an important void in the existing literature.

Table 1. Some examples of research using NMD and WASPAS methods

Author(s)	Subject for which the method is used
NMD	
Bağcı and Sarıay (2021)	Determination of the role of market capitalisation and public market capitalisation in business performance
Ergun et al. (2022)	Determination of the transaction performance of companies operating in the licensed warehousing sector
Kılıçarslan (2023a)	Financial performance analysis of renewable energy sector companies
Kılıçarslan (2023b)	Financial performance analysis of companies traded in the stock fund index
Bulut (2024)	Comparison of countries in the European region according to risk factors for non-communicable diseases
Öner and Bağcı (2025)	Financial performance analysis of Islamic banks in the Organisation of Islamic Cooperation Countries
WASPAS	
Author(s)	**Subject for which the method is used**
Zavadskas et al. (2013)	Selection of facade cladding for public buildings
Chakraborty and Zavadskas (2014)	In the production decision problem
Karabašević et al. (2016)	Personnel selection
Urosevic et al. (2017)	Selection of sales managers in the tourism sector
Pamucar et al. (2019)	Evaluation of logistics providers
Karaca et al. (2020)	Determination of the financial performance of banks in Türkiye
Çilek and Karavardar (2021)	Analysis of the banking performance of cities in the Black Sea Region
Kırhasanoğlu and Özdemir (2022)	Evaluation of the Covid-19 period financial performance of football clubs traded in Borsa Istanbul
Medetoğlu et al. (2023)	Determination of the financial performance of companies in the accommodation sector in Borsa Istanbul
Kara et al. (2023)	Evaluation of the website performance of super league football clubs
Aydın et al. (2024)	Evaluation of the performance of electric cars
Kandemir et al. (2024)	Evaluation of the level of preferability of using block chain technology according to sectors
Dumlu (2025)	Road transport vehicle selection for logistics company

3. Methodology

The aim of this study is to determine the importance weights of return-related criteria affecting the selection of sustainability-themed funds and to rank their performance. Criterion weights are established using the Normalized Maximum Difference (NMD) method, while the Weighted Aggregated Sum Product Assessment (WASPAS) approach is employed to rank the sustainability-themed funds. NMD is chosen for this study because it offers computational simplicity and distinctiveness from other weighting methods under conditions of uncertainty regarding criterion importance and weights. WASPAS is preferred both for its frequent application in financial performance evaluation and for combining the two well-known MCDM techniques-Weighted Sum Method (WSM) and Weighted Product Method (WPM). Moreover, conducting sensitivity analyses on the two methods embedded within WASPAS is expected to contribute valuable insights to the literature.

3.1. NMD method

In literature reviews, several mathematically designed standard weighting methods such as Entropy, CRITIC, and AHP are commonly used. This method can be reliably applied in cases where the importance levels of criteria cannot be determined in terms of their significance (Bulut 2022). Moreover, in terms of implementation, the method is shorter and more practical compared to others. These aspects differentiate the method from other commonly used weighting approaches. The NMD method is applied using the steps presented in Table 2 (Bulut 2017; Bulut 2022; Kılıçarslan and Özmen 2023; Örtlek and Kılıçarslan 2025).

Table 2. NMD method application steps

Step	Equation	
Preparation of decision matrix	$X_{ij} = \begin{Bmatrix} x_{1,1} & x_{1,2} & x_{1,3} & x_{1,c} \\ x_{2,1} & x_{2,2} & x_{2,3} & x_{2,c} \\ x_{3,1} & x_{3,2} & x_{3,3} & x_{3,c} \\ x_{r,1} & x_{r,2} & x_{r,3} & x_{r,4} \end{Bmatrix}$	(1)
Preparation of ratio matrix	$T = \sum_{j=1}^{c} X_{ij} \quad t = \{c_1, c_2, \dots, c_c\}$ $R_{ij} = \begin{Bmatrix} r_{1,1} & r_{1,2} & r_{1,c} \\ r_{2,1} & r_{2,2} & r_{2,c} \\ r_{3,1} & r_{3,2} & r_{3,c} \end{Bmatrix}$	(2)
Calculation of normalised values	$max = \{max_1, \dots, max_c\}$ $A = \frac{\sum_{j=1}^{c} r_{ij}}{r} \; S = \frac{r_{ij}-a_i}{\sqrt{\sum(r_{ij}-a_i)^2}} \; N = \frac{max_i - a_i}{s_i}$	(3)
Calculation of weights of criteria	$W = \frac{n_i}{\sum_{i=1}^{c} n_i}$	(4)

Note: X_{ij}; decision matrix, T; criterion subtotal cluster value, R_{ij};ratio matrix, A; average of the values of the criterion, S; standard deviation, N; standardised value of each criterion, w; criterion weight value.

NMD is chosen for this study because it offers computational simplicity and distinctiveness from other weighting methods under conditions of uncertainty regarding criterion importance and weights. Unlike subjective weighting methods such as AHP, NMD provides an objective approach to determine criterion weights, which is crucial for ensuring the impartiality and replicability of the evaluation process, especially in a sensitive area like sustainable finance where diverse stakeholder perspectives exist. Moreover, in terms of implementation, the method is shorter and more practical compared to others, making it efficient for analysing multiple criteria without extensive computational burden. These aspects differentiate the method from other commonly used weighting approaches, providing a robust and transparent mechanism for criterion weighting.

3.2. WASPAS method

The WASPAS approach, proposed by Zavadskas et al. (2012), combines two different techniques: additive and multiplicative. In the WASPAS method, the λ value representing the weight of the WSM and WPM methods can be determined by the researchers within the range of 0 to 1; however, it is commonly chosen in a way that treats both parameter methods as equally important. In this context, the alternative with the highest score is considered the best option for the MCDM problem. The WASPAS method is implemented using the steps presented in Table 3 (Pala 2022).

WASPAS is preferred both for its frequent application in financial performance evaluation and for combining the two well-known MCDM techniques-Weighted Sum Method (WSM) and Weighted Product Method (WPM). This hybrid approach allows WASPAS to achieve a higher level of accuracy and stability in ranking alternatives compared to using WSM or WPM alone, as it leverages the strengths of both methods in handling different types of decision-making scenarios. Its ability to provide a comprehensive and balanced evaluation makes it particularly suitable for assessing the multifaceted performance of sustainability-themed mutual funds, which involve both financial and non-financial criteria. Moreover, conducting sensitivity analyses on the two methods embedded within WASPAS is expected to contribute valuable insights to the literature by demonstrating the robustness of the rankings under varying conditions and providing a deeper understanding of the decision-making process.

Table 3. WASPAS method application steps

Step	Equation	
Preparation of the decision matrix	$X_{ij} = \begin{Bmatrix} x_{1,1} & x_{1,2} & x_{1,3} & x_{1,c} \\ x_{2,1} & x_{2,2} & x_{2,3} & x_{2,c} \\ x_{3,1} & x_{3,2} & x_{3,3} & x_{3,c} \\ x_{r,1} & x_{r,2} & x_{r,3} & x_{r,4} \end{Bmatrix}$	(5)
Calculation of the normalized values	$z_{ij} = \frac{x_{ij}}{x_j^{max}}$ benefit criterion	(6)
	$z_{ij} = \frac{x_j^{min}}{x_{ij}}$ cost criterion	(7)
Calculation of the weighted sum model	$WSM_i = \sum_{j=1}^{m} w_j z_{ij} \; i = 1, \dots, n$	(8)
Calculation of the weighted product model	$WPM_i = \prod_{j=1}^{m} (z_{ij})^{w_j} \; i = 1, \dots, n$	(9)
Calculation of the criteria weights	$Q_i = (\lambda \mathrm{WSM}_i + (1 - \lambda) WPM_i) \; i = 1, \dots, n$	(10)

4. Data set, application process and findings

The dataset of the study consists of data from May 2022 to April 2025 for sustainability-themed variable umbrella funds, fund-of-funds umbrella funds, and equity umbrella funds traded on TEFAS. A total of 16 sustainability-themed funds traded on TEFAS with data available for the past three years were included: 5 variable umbrella funds, 4 fund-of-funds umbrella funds, and 7 equity umbrella funds. These funds were categorized into three different groups according to their umbrella fund type, as presented in Table 4.

Table 4. Sustainability-themed funds included in the scope of the study

Fund Code	Fund	Umbrella Fund Type
GZH	Garanti Portföy Temiz Enerji Değişken Fon	**Volatile Umbrella Fund**
TMC	İş Portföy Tema Değişken Fon	
VCY	Ak Portföy Elektrikli Ve Otonom Araç Teknolojileri Değişken Fon	
YJH	Yapı Kredi Portföy Temiz Enerji Değişken Fonu	
YLO	Yapı Kredi Portföy Elektrikli Araçlar Değişken Fon	
DHM	Deniz Portföy ESG-Sürdürülebilirlik Fon Sepeti Fonu	**Fund-of-funds umbrella funds**
GZV	Garanti Portföy ESG Sürdürülebilirlik Fon Sepeti Fonu	
OLD	QNB Portföy Temiz Enerji ve Su Fon Sepeti Fonu	
TJF	TEB Portföy Sürdürülebilirlik Fon Sepeti Fonu	
AOY	Ak Portföy Alternatif Enerji Yabancı Hisse Senedi Fonu	**Equity Umbrella Fund**
DLD	Deniz Portföy Sürdürülebilirlik Hisse Senedi Fonu	
GZR	Garanti Portföy Sürdürülebilirlik Hisse Senedi (TL) Fonu	
HMS	HSBC Portföy Sürdürülebilirlik Hisse Senedi (TL) Fonu	
IFN	ICBC Turkey Portföy Sürdürülebilirlik Hisse Senedi Fonu	
IHK	İş Portföy İş'te Kadın Hisse Senedi (TL) Fonu	
YLE	Yapı Kredi Portföy Bıst Sürdürülebilirlik Endeksi Hisse Senedi Fonu	

Source: www.tefas.gov.tr

The criteria used to determine the performance ranking of the sustainability-themed investment funds utilized in this study are presented in Table 5.

Table 5. Performance criteria used in the analysis

Criterion Number	Criterion Name	Criterion Definition	Benefit/ Cost
C1	1 Month (%)	Sustainability Funds Last 1 Month Return (%)	Positive
C2	3 Months (%)	Sustainability Funds Last 3 Months Return (%)	Positive
C3	6 Months (%)	Sustainability Funds Last 6 Months Return (%	Positive
C4	New Year (%)	Sustainability Funds Return (%) from 1 January 2025	Positive
C5	1 Year (%)	Sustainability Funds Last 12 Months Return (%)	Positive
C6	3 Years (%)	Sustainability Funds Last 36 Months Return (%)	Positive
C7	Change in Portfolio Size (%)	Last 36 Months Portfolio Size Change (%)	Positive
C8	Change in Number of Shares (%)	Last 36 Months Number of Shares Change (%)	Positive

The decision matrix obtained from the data on sustainability-themed mutual funds for the period May 2022-April 2025 is shown in Table 6.

Table 6. Sustainability themed mutual funds decision matrix

Fund Code	1 Month (%)	3 Months (%)	6 Months (%)	New Year (%)	1 Year (%)	3 Years (%)	Change in Portfolio Size (%)	Change in Number of Shares (%)
GZH	-0.355	-0.233	-1.721	-1.148	-4.938	106.256	-50.2	-75.85
TMC	-0.685	-0.688	8.149	2.267	29.091	210.677	2228	649.48
VCY	0.93	-2.489	3.940	-0.612	4.709	98.38	21.42	-38.79
YJH	-1.103	-3.358	-5.146	-4.604	-3.305	79.457	-42.2	-67.8
YLO	0.587	-3.694	3.368	-1.149	12.997	176.57	81.4	-34.41
DHM	-2.404	-7.015	1.919	-4.407	9.279	230.226	931.3	212.29
GZV	0.201	1.881	6.468	4.353	17.147	195.373	-45	-81.36
OLD	-0.524	-4.021	-1.806	-3.431	-1.09	115.673	-56.8	-79.96
TJF	-1.949	-3.323	6.002	-0.435	6.285	148.653	-59.2	-83.6
AOY	1.656	5.528	-5.417	4.377	-8.525	28.391	-27.9	-43.82
DLD	-4.404	-9.473	1.195	-6.427	-4.38	300.294	1573	317.88
GZR	-4.984	-8.786	3.466	-5.759	-1.712	355.845	894.2	118.09
HMS	-3.369	-9.079	6.257	-5.056	1.955	490.324	777.1	48.58
IFN	-4.412	-8.85	0.309	-7.317	-5.614	513.543	703.6	30.97
IHK	-5.264	-12.461	3.036	-8.237	6.119	588.588	5632	732.48
YLE	-3.424	-8.395	3.169	-5.611	-2.466	390.616	445.5	11.190

When Table 6 is examined, it is observed that the highest returns were recorded by the AOY fund in the 1-month, 3-month, and year-to-date periods until April 30, 2025 (1.6556%, 5.5279%, and 4.3771%, respectively); by the TMC fund in the 6-month and 1-year periods (8.1493% and 29.0905%, respectively); and by the IHK fund in the 3-year period (588.588%). The lowest returns were recorded by the IHK fund in the 1-month, 3-month, and year-to-date periods until April 30, 2025 (-5.2635%, -12.461%, and -8.2371%, respectively); and by the AOY fund in the 6-month, 1-year, and 3-year periods (-5.4173%, -8.5249%, and -28.3913%, respectively). The highest increase in portfolio size (5,632.35%) and the highest increase in the number of shares (732.48%) occurred in the IHK fund. The largest decrease in portfolio size (-59.2%) and the largest drop in the number of shares (-83.6%) occurred in the TJF fund.

While constructing the decision matrix, negative values were observed in the evaluation criteria except for the 3-year return. Therefore, all values in the decision matrix were adjusted using the Z-Score method through Equation 11 and Equation 12 (Zhang et al. 2014; Ünal 2025).

$$x_{ij}=\frac{X_{ij}-\overline{X}_i}{S_i} \tag{11}$$

$$x'_{ij}=x_{ij}+A \qquad A>\left|minx_{ij}\right| \tag{12}$$

The decision matrix of sustainability-themed investment funds adjusted using the Z-Score method is presented in Table 7.

Table 7. Adjusted decision matrix of sustainability-themed investment funds

Fund Code	1 Month (%)	3 Months (%)	6 Months (%)	New Year (%)	1 Year (%)	3 Years (%)	Change in Portfolio Size (%)	Change in Number of Shares (%)
GZH	2.562	2.815	0.950	2.291	1.051	1.045	1.304	1.212
TMC	2.415	2.721	3.418	3.153	4.483	1.658	2.875	4.030
VCY	3.133	2.348	2.365	2.426	2.024	0.999	1.353	1.356
YJH	2.229	2.167	0.094	1.418	1.215	0.888	1.310	1.243
YLO	2.981	2.098	2.223	2.291	2.860	1.458	1.395	1.373
DHM	1.650	1.410	1.860	1.468	2.485	1.772	1.981	2.332
GZV	2.809	3.253	2.998	3.680	3.278	1.568	1.308	1.191
OLD	2.487	2.030	0.929	1.714	1.439	1.100	1.300	1.196
TJF	1.852	2.175	2.881	2.471	2.183	1.294	1.298	1.182
AOY	3.456	4.009	0.026	3.686	0.689	0.588	1.319	1.337
DLD	0.760	0.900	1.679	0.957	1.107	2.183	2.423	2.742
GZR	0.502	1.042	2.247	1.126	1.376	2.509	1.955	1.966
HMS	1.220	0.982	2.945	1.304	1.746	3.298	1.874	1.695
IFN	0.756	1.029	1.458	0.733	0.983	3.435	1.824	1.627
IHK	0.377	0.281	2.140	0.500	2.166	3.875	5.221	4.353
YLE	1.196	1.123	2.173	1.164	1.300	2.713	1.646	1.550

In the following sections, all the sustainability-themed funds included in the study were first analyzed. Subsequently, the performances of variable umbrella funds, fund-of-funds umbrella funds, and equity umbrella funds were analyzed separately based on fund type.

4.1. NMD method findings

According to the NMD method, the decision matrix presented in Table 7 was normalized using Equation 2. Then, using the models in Equation 3, the normalized criterion values were obtained by applying the maximum criterion value, mean, and standard deviation. Finally, with the help of Equation 4, the weights of the criteria were determined and presented in Table 8.

Table 8. Weights of evaluation criteria for sustainability funds

	C1	C2	C3	C4	C5	C6	C7	C8
Maximum Criterion Value	0.114	0.132	0.112	0.121	0.148	0.128	0.172	0.143
Average	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063
Standard Deviation	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033
Normalized Criterion Values	1.557	2.110	1.519	1.787	2.584	1.976	3.322	2.454
Criterion Weights	0.090	0.122	0.088	0.103	0.149	0.114	0.192	0.142

It is observed that there is a linear relationship among the normalized or, in other words, standardized criterion values presented in Table 8. Accordingly, in the NMD method, if many alternatives have high scores for a particular criterion, the weight of that criterion in the decision-making problem increases.

This situation is most evident in C7 (Change in Portfolio Size %), which has the highest weight, whereas C3 (6-Month Return %) displays the opposite structure and has the lowest importance.

The implementation steps of the NMD method were applied separately according to the fund type of the sustainability-themed funds. The criterion weights for variable umbrella funds are presented in Table 9, for fund-of-funds umbrella funds in Table 10, and for equity umbrella funds in Table 11.

Table 9. Weights of evaluation criteria for variable umbrella funds

	C1	C2	C3	C4	C5	C6	C7	C8
Maximum Criterion Value	0.364	0.359	0.365	0.381	0.405	0.381	0.438	0.438
Average	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200
Standard Deviation	0.133	0.133	0.133	0.133	0.133	0.133	0.133	0.133
Normalized Criterion Values	1.230	1.191	1.238	1.358	1.536	1.356	1.786	1.786
Criterion Weights	0.107	0.104	0.108	0.118	0.134	0.118	0.156	0.156

According to the findings for sustainable-themed variable umbrella funds in Table 9, the criteria with the highest importance are C7 and C8 (Portfolio size change % and number of shares change %), while the criterion with the lowest importance is C2 (Last 3 months return %).

Table 10. Weights of evaluation criteria for fund-of-funds umbrella funds

	C1	C2	C3	C4	C5	C6	C7	C8
Maximum Criterion Value	0.467	0.510	0.415	0.511	0.486	0.470	0.539	0.539
Average	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250
Standard Deviation	0.192	0.192	0.192	0.192	0.192	0.192	0.192	0.192
Normalized Criterion Values	1.128	1.352	0.856	1.355	1.225	1.143	1.500	1.500
Criterion Weights	0.112	0.134	0.085	0.135	0.122	0.114	0.149	0.149

According to the findings for sustainable-themed fund basket umbrella funds in Table 10, the criteria with the highest importance are C7 and C8 (Portfolio size change % and number of shares change %), while the criterion with the lowest importance is C3 (Last 6 months return %).

Table 11. Weights of evaluation criteria for equity umbrella funds

	C1	C2	C3	C4	C5	C6	C7	C8
Maximum Criterion Value	0.297	0.300	0.231	0.299	0.263	0.223	0.300	0.289
Average	0.143	0.143	0.143	0.143	0.143	0.143	0.143	0.143
Standard Deviation	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071
Normalized Criterion Values	2.162	2.205	1.238	2.191	1.681	1.125	2.195	2.050
Criterion Weights	0.146	0.149	0.083	0.148	0.113	0.076	0.148	0.138

According to the findings for sustainable-themed equity umbrella funds in Table 11, the criterion with the highest importance is C2 (Last 3 months return %), while the criterion with the lowest importance is C6 (Last 36 months return %).

When comparing the importance weights of sustainable-themed variable umbrella funds, fund basket umbrella funds, and equity funds, it is observed that the criteria with the highest and lowest importance differ, and there are also changes in the ranking of importance.

4.2. WASPAS method findings

After determining the criterion weights for the decision problem using the NMD method, the WASPAS method was applied to rank the fund performances of sustainability-themed funds. First, the normalized decision matrix was obtained from the decision matrix in Table 7 using Equation 6. Using the values of the normalized decision matrix, the final score values of the intermediary institutions were calculated with the WASPAS methods -WSM, WPM, and λ = 0.5- using Equations 8, 9, and 10, respectively. The results are presented in Table 12.

Table 12. WSM, WPM, and WASPAS ranking results of sustainability-themed funds

	WSM		WPM		WASPAS	
Fund Code	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**
GZH	0.394	11	0.352	12	0.373	12
TMC	0.757	1	0.728	1	0.742	1
VCY	0.472	5	0.429	5	0.450	6
YJH	0.321	16	0.263	15	0.292	16
YLO	0.497	4	0.461	3	0.479	4
DHM	0.458	6	0.452	4	0.455	5
GZV	0.594	3	0.519	2	0.557	2
OLD	0.365	14	0.343	13	0.354	13
TJF	0.455	7	0.418	6	0.436	7
AOY	0.448	9	0.258	16	0.353	14
DLD	0.397	10	0.365	10	0.381	9
GZR	0.390	12	0.359	11	0.374	11
HMS	0.453	8	0.417	7	0.435	8
IFN	0.363	15	0.324	14	0.344	15
IHK	0.607	2	0.415	8	0.511	3
YLE	0.388	13	0.367	9	0.377	10

According to the results presented in Table 12, the TMC variable umbrella fund ranked first, followed by the GZV fund of funds umbrella fund and the IHK equity umbrella fund. TMC, which had the best or relatively high scores across all criteria, was identified as the best alternative among sustainability-themed funds using the WASPAS method, which is considered meaningful. The funds with the lowest ranking scores were found to be the YJH variable umbrella fund, the IFN equity umbrella fund, and the AOY equity umbrella fund, respectively.

WASPAS method application steps were individually implemented according to the fund types of sustainability-themed funds. The ranking results for variable umbrella funds are presented in Table 13, the ranking results for fund of funds umbrella funds are shown in Table 14, and the ranking results for equity umbrella funds are provided in Table 15.

Table 13. Variable umbrella funds WSM, WPM, and WASPAS ranking results

	WSM		WPM		WASPAS	
Fund Code	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**
GZH	0.407	4	0.365	4	0.386	4
TMC	0.915	1	0.872	1	0.893	1
VCY	0.496	3	0.458	3	0.477	3
YJH	0.198	5	0.148	5	0.173	5
YLO	0.524	2	0.474	2	0.499	2

According to the results presented in Table 13, the TMC fund ranks first, followed by the YLO fund and the VCH fund. The funds with the lowest ranking scores are found to be the YJH fund and the GZH fund, respectively.

Table 14. Fund of funds umbrella funds WSM, WPM, and WASPAS ranking results

	WSM		WPM		WASPAS	
Fund Code	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**
DHM	0.569	2	0.391	2	0.480	2
GZV	0.756	1	0.665	1	0.710	1
OLD	0.272	4	0.168	4	0.220	4
TJF	0.421	3	0.391	3	0.406	3

According to the results presented in Table 14, the GZV fund ranks first, followed by the DHM fund. The funds with the lowest ranking scores are found to be the OLD fund and the TJF fund, respectively.

Table 15. Equity umbrella funds WSM, WPM, and WASPAS ranking results

	WSM		WPM		WASPAS	
Fund Code	**Score**	**Rank**	**Score**	**Rank**	**Score**	**Rank**
AOY	0.551	2	0.316	7	0.433	6
DLD	0.463	6	0.456	4	0.459	5
GZR	0.467	5	0.454	5	0.460	4
HMS	0.544	3	0.514	2	0.529	2
IFN	0.422	7	0.407	6	0.414	7
IHK	0.661	1	0.558	1	0.609	1
YLE	0.470	4	0.457	3	0.463	3

According to the results presented in Table 15, the IHK fund ranks first, followed by the HMS fund and the YLE fund. The funds with the lowest ranking scores are found to be the IFN fund, the AOY fund, and the DLD fund, respectively.

4.3. Sensitivity analysis

In this study, a sensitivity analysis was conducted to observe the impact of different weight levels of the WSM and WPM methods within the WASPAS approach on the results.

Table 16. WASPAS scores of sustainability-themed funds with different λ values

Fund Code	**λ=0**	**λ=0.1**	**λ=0.2**	**λ=0.3**	**λ=0.4**	**λ=0.6**	**λ=0.7**	**λ=0.8**	**λ=0.9**	**λ=1.0**
GZH	0.352	0.356	0.360	0.364	0.369	0.377	0.381	0.386	0.390	0.394
TMC	0.728	0.731	0.733	0.736	0.739	0.745	0.748	0.751	0.754	0.757
VCY	0.429	0.433	0.437	0.442	0.446	0.455	0.459	0.464	0.468	0.472
YJH	0.263	0.269	0.275	0.281	0.286	0.298	0.304	0.310	0.316	0.321
YLO	0.461	0.464	0.468	0.472	0.475	0.482	0.486	0.490	0.493	0.497
DHM	0.452	0.453	0.453	0.454	0.454	0.456	0.456	0.457	0.458	0.458
GZV	0.519	0.527	0.534	0.542	0.549	0.564	0.572	0.579	0.587	0.594
OLD	0.343	0.345	0.348	0.350	0.352	0.357	0.359	0.361	0.363	0.365
TJF	0.418	0.422	0.426	0.429	0.433	0.440	0.444	0.447	0.451	0.455
AOY	0.258	0.277	0.296	0.315	0.334	0.372	0.391	0.410	0.429	0.448
DLD	0.365	0.368	0.372	0.375	0.378	0.384	0.387	0.390	0.393	0.397
GZR	0.359	0.362	0.365	0.368	0.371	0.377	0.380	0.384	0.387	0.390
HMS	0.417	0.420	0.424	0.428	0.431	0.439	0.442	0.446	0.450	0.453
IFN	0.324	0.328	0.332	0.336	0.340	0.347	0.351	0.355	0.359	0.363
IHK	0.415	0.434	0.453	0.473	0.492	0.530	0.550	0.569	0.588	0.607
YLE	0.367	0.369	0.371	0.373	0.375	0.379	0.382	0.384	0.386	0.388

In Table 16, the WASPAS method was applied using different λ values, and the score values of the sustainability-themed funds were presented. As expected, no significant variation was observed in the rankings of the sustainability-themed funds for any λ value.

According to Table 16, as the λ value increases for all sustainability-themed investment funds, the scores also increase. This indicates that the additive model calculates higher scores. The funds showing the strongest score increases are IHK (+0.192) and AOY (+0.190), making these two funds the options that gain the most advantage from the additive model. The fund with the least change in score is DHM (+0.006), whose score changes very little according to the model and shows similar performance in both the multiplicative and additive models. Figure 1 illustrates how the WASPAS scores of each sustainability-themed investment fund change according to the λ value.

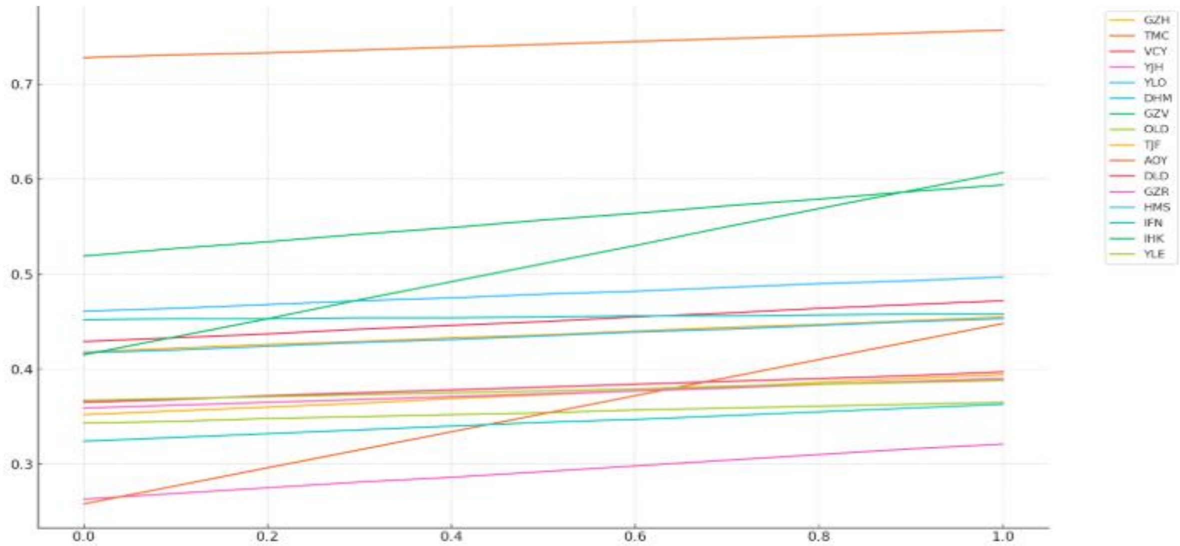

Figure 1. WASPAS score trends of funds according to λ value

The graph illustrates the trend of WASPAS scores for each investment fund as the value of λ changes. In Figure 1, TMC consistently achieves the highest score across all λ values, indicating that TMC is consistently strong in both the multiplicative and additive models. Most alternatives show a steady increase in scores as the λ value rises. While some alternatives maintain stable performance, others experience more noticeable fluctuations. A comparison of all λ values and fund scores is presented in colour in Figure 2.

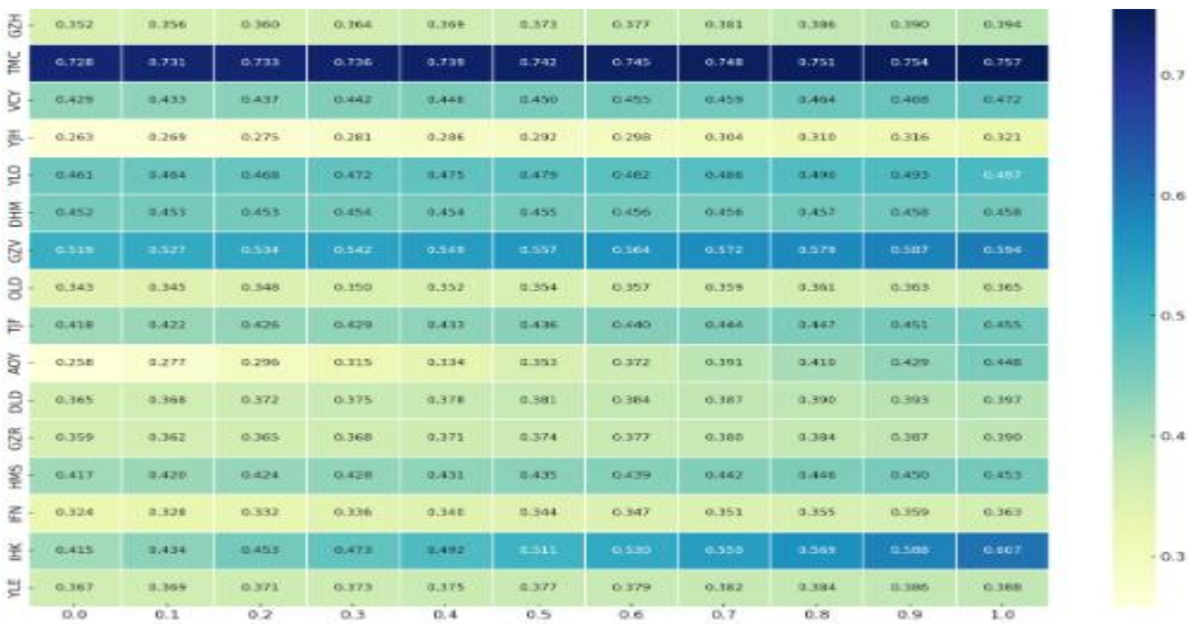

Figure 2. Heatmap of WASPAS scores of funds according to λ values

The heatmap shows the WASPAS scores of each sustainable investment fund at different λ values. As the colour intensity increases (towards dark blue), the score magnitude increases. Notably, some investment funds remain more stable against changes in λ, while others exhibit significant variations.

A stability analysis based on standard deviation was conducted to determine which sustainability-themed investment fund remained the most stable against changes in λ under all conditions, and the results are presented in Figure 3.

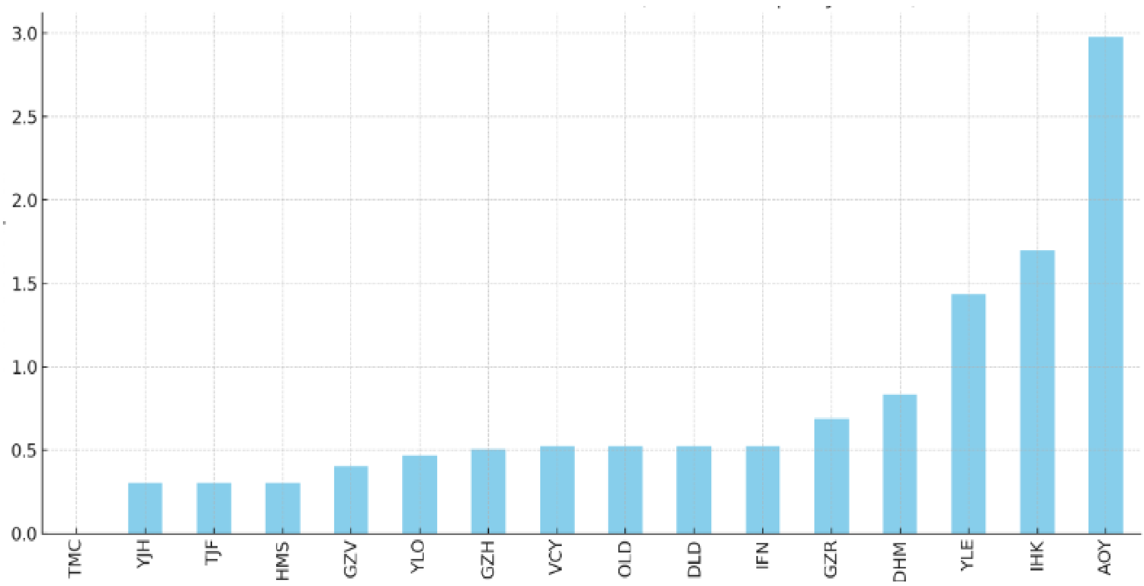

Figure 3. Ranking stability of sustainability-themed funds

Figure 3 shows the standard deviation (variability) of each investment fund's ranking with respect to changes in λ. The TMC fund was identified as the most stable fund, with a constant ranking that remained in the top position under all conditions. The AOY fund was found to have the most variable ranking, significantly improving its position as the λ value increased. Funds such as IHK and YLE were observed to have a moderate level of fluctuation.

The top five sustainability-themed investment funds based on the selected λ values are presented in Table 17.

Table 17. Rankings of sustainability-themed funds for selected λ values

λ Value	1.	2.	3.	4.	5.
λ = 0.0	TMC	GZV	YLO	DHM	VCY
λ = 0.5	TMC	GZV	IHK	YLO	DHM
λ = 1.0	TMC	IHK	GZV	YLO	VCY

As shown in Table 17, the TMC fund demonstrated its consistency by ranking first across all λ values. GZV, YLO, and IHK are also among the other strong sustainability-themed investment funds. Notably, GZV's score increases significantly as λ rises, indicating a high sensitivity to the λ parameter. The IHK fund showed a strong upward trend, moving from 8th place at λ = 0 to 2nd place at λ = 1. As the λ value increases—particularly beyond 0.5—some funds rapidly gain in ranking. This suggests that with the growing influence of the additive model, these investment funds become more advantageous. Conversely, some funds rapidly lose ranking as λ increases (especially after 0.5), indicating that the decreasing influence of the multiplicative model makes these funds less favourable.

5. Conclusion and evaluation

This study offers significant contributions to the academic literature by comprehensively examining the return performance dynamics of 16 sustainability-themed umbrella funds traded on TEFAS between

May 2022 and April 2025. The research's key originality lies in the integration of the Normalized Maximum Deviation (NMD) method for objective weighting of criteria within the sustainable finance context and its combination with the WASPAS technique. This methodological choice enhances transparency and reproducibility by offering a robust, data-driven alternative to subjective weighting practices in fund evaluations.

The WASPAS method, which synergistically combines the Weighted Sum Model (WSM) and the Weighted Product Model (WPM), allows for a more balanced and reliable ranking of multifaceted investment vehicles. Sensitivity analyses conducted under varying lambda (λ) values further reinforce the validity of the results, particularly highlighting the consistent top-tier performance of funds such as TMC, regardless of model assumptions.

The findings provide critical insights into investor behavior and market dynamics within Türkiye's emerging sustainable finance ecosystem. The prioritization of portfolio size and changes in share count (C7 and C8) over short-term returns, as revealed by the NMD results, indicates a strong investor preference for liquidity and long-term growth potential. This observation challenges traditional short-term performance metrics and reflects the unique nature of sustainability-oriented investment behavior.

Furthermore, the variation in the relative importance of criteria across different fund types—such as variable umbrella funds, fund-of-funds, and equity umbrella funds—emphasizes the need for tailored investment strategies. This offers practical guidance to fund managers seeking to align portfolio designs with distinct investor expectations. Notably, the consistently strong performance of diverse funds like TMC, GZV, and IHK supports the notion that sustainability-focused strategies can deliver competitive financial returns without compromising ethical standards. This challenges the widespread assumption that sustainable investing inevitably leads to lower financial performance and encourages broader adoption of ESG principles.

For policymakers and regulators, the study presents several important implications. The evident investor interest in liquidity and long-term value creation necessitates more frequent and transparent reporting of fund size and share count changes. Accordingly, there is a pressing need to strengthen regulatory frameworks and expand reporting standards to support the healthy development of the sustainable finance market. Moreover, the study advocates the creation of investor education programs to help bridge the gap between short-term market perceptions and the long-term value propositions of sustainable investments. Integrating the quantitative indicators developed in this study into ESG reporting standards could significantly enhance market transparency and enable more informed investment decisions. In doing so, the study lays the groundwork for more effective policies that support both the growth and integrity of the sustainable finance ecosystem.

Future research may extend this study in several directions. First, applying alternative MCDM techniques could allow for a comparison of consistency and sensitivity, further validating the methodological approach. Second, expanding the analysis period to include shorter or longer timeframes would facilitate the examination of temporal trends and robustness. Third, incorporating qualitative ESG dimensions—such as carbon footprint or social impact scores—would add depth to performance assessments, creating a more holistic view of sustainability. Finally, conducting comparative studies with sustainability-themed funds in other emerging markets would uncover both regional distinctions and shared trends, contributing to a more comprehensive global understanding of sustainable investment performance.

Declaration of competing interest

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

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Digital futures in banking: Empirical insights from deposit and participation sectors

Erhan AKARDENİZ[1]

HIGHLIGHTS

[1] Gaziantep University, Social SciencesVocational School, Gaziantep, Türkiye, erhanakardeniz@gantep.edu.tr

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ABSTRACT

The aim of this research is to examine the effects of digitalization between participation banks and deposit banks in Türkiye from 2010 to 2024. Within the 2010-2024 period, analyses were conducted using quarterly data from a total of 37 deposit banks and 9 participation banks operating in Türkiye, categorized as foreign capital, public capital, and private capital. The Toda-Yamamoto causality method was used in the study. It is observed that the impact of digitalization on banking profitability varies according to the type of bank. In deposit banks, it is understood that digitalization is a strong tool in terms of efficiency and income generation; whereas, in participation banks, the impact of digitalization is more shaped by external macroeconomic conditions. Despite the fact that digitalization has increased operational efficiency post-pandemic, macroeconomic uncertainties have differentiated its effects. In conclusion, it is recommended that banks shape their digital strategies in line with profitability, efficiency, and flexibility goals, while regulatory institutions provide a legal framework compatible with digitalization.

1. Introduction

The rapid transformation in digital technologies over the past decade has brought about profound structural changes in the global financial system. Especially the banking sector has been one of the areas where this transformation has been most deeply felt. Innovative applications such as mobile banking, internet branches, digital wallets, and remote customer acquisition have redefined the operational functioning of banks, changed customer behaviors, and led to the emergence of new dynamics in the profitability structure of banks. In this context, digitalization should be regarded not only as a technological advancement but also as a structural transformation that affects the strategic positioning of banks. From a theoretical perspective, digitalization affects bank profitability through several channels. According to cost efficiency theory, the adoption of digital banking reduces branch dependency and operational costs, thereby enhancing efficiency. At the same time, customer relationship and intermediation theories suggest that digital channels expand customer bases, strengthen loyalty, and increase cross-selling opportunities, which enhance revenues. On the other hand, competition and market structure theories underline that digitalization fosters market contestability, potentially narrowing interest margins and reducing traditional profit channels. Finally, risk management theories emphasize that while digital tools improve monitoring, credit risk assessment, and transparency, they also expose banks to cyber risks and operational vulnerabilities.

These mechanisms demonstrate that the effects of digitalization on bank profitability are multifaceted and potentially heterogeneous across different types of banks.

The digitalization process that gained momentum in Türkiye from the early 2010s has changed the service delivery methods of both private and public capital banks. Especially in the post-pandemic period, the more intensive use of digital channels has accelerated the shift of banking transactions outside physical branches. However, the effects of digitalization on the banking sector can vary according to the types of banks. Deposit banks generally have a wider customer base, a variety of products, and digital infrastructure; whereas participation banks, with their alternative models operating in accordance with interest-free finance principles, are adapting to this transformation on a more limited scale and with unique structures. This differentiation suggests that the impact of digitalization on bank profitability is not homogeneous. Theoretically, this heterogeneity can be explained by the differences in business models: traditional interest-based banks can leverage digitalization to expand lending and fee-based services, while participation banks face constraints in product diversification and must adapt digital tools to Sharia-compliant frameworks, which may limit efficiency gains but create niche competitive advantages. Particularly in developing economies such as Türkiye, the sectoral consequences of digitalization should be analyzed within a framework that considers both the structural characteristics of different bank types and prevailing macroeconomic conditions.

Although there is a considerable body of literature on the relationship between digitalization and bank performance, comparative studies examining the differences between participation and deposit banks remain scarce. Although numerous studies have examined the relationship between digitalization and bank performance in various contexts, most of them have focused on advanced economies or have treated the banking sector as a homogeneous whole. For instance, research by Chen et al. (2024) and Ozili (2018) primarily investigates digital banking's role in improving operational efficiency and customer reach, yet does not account for differences in institutional structures such as those between interest-based and interest-free banking models. In the case of Türkiye, empirical studies on digitalization in banking such as those by Yıldırım (2020) and Kaya (2022) tend to focus on deposit banks, leaving participation banks largely underexplored. Moreover, few studies explicitly integrate macroeconomic variables like the country risk premium or inflation into models analyzing digitalization's effect on profitability. This gap limits the ability to formulate differentiated policy recommendations for distinct bank types. Theoretically, integrating macroeconomic dynamics into digitalization analysis can be grounded in macroeconomic transmission theories, where variables such as inflation, interest rates, and risk premia interact with banks' profitability channels and may amplify or dampen the efficiency and competition effects of digital transformation.

By incorporating both bank-specific digitalization indicators and macroeconomic conditions, and by applying a comparative framework between participation and deposit banks, the present study aims to address this void in the literature. In this context, the motivation of the present study lies in addressing this research gap by systematically investigating the heterogeneous effects of digitalization on bank profitability. By doing so, the study aims to provide a clearer and more convincing articulation of the rationale behind the research and its intended contributions to both theory and practice.

This study covers participation and deposit banks operating in Türkiye for the period 2010-2024; it analyzes the impact of variables such as the number of digital banking customers, interest rates, country risk premium, and inflation on bank profitability using panel data and the Toda-Yamamoto causality method. Thus, it will be revealed how the impact of digitalization on financial performance is shaped both directly and in a macroeconomic context. The study is expected to contribute to a better understanding of the digital transformation process in the banking sector and to develop recommendations for policymakers. This study aims to examine the impact of the level of digital banking on bank profitability by comparing participation and deposit banks operating in Türkiye during the 2010-2024 period using the panel data method. Thus, it will be revealed whether the relationship between digitalization and profitability varies according to the types of banks, and the reflections of the digital transformation process on financial performance will be empirically tested. This research aims not only to contribute to the academic literature but also to provide policy-developing information for bank managers, regulatory institutions, and financial organizations planning technology investments.

The contributions of the study to the field are as follows: (i) To examine the impact of the digitalization levels of participation and deposit banks operating in Türkiye during the 2010-2024 period on bank profitability using the panel data method. (ii) At the same time, it will be revealed whether this relationship varies in direction and magnitude among different types of banks, and which internal or external factors are effective. (iii) The topic will be examined using the Toda-Yamamoto approach with a new method.

The study consists of four sections. In the first section, the rapid development of financial technologies and their impact on the banking sector is discussed; in the second section, the importance and effect of digitalization on bank profitability is highlighted, with a specific focus on deposit and participation banking. In the third section, evaluations were made regarding the findings obtained from the research conducted in Türkiye. Then, the models were established. In the fourth chapter, the results presented by the models were evaluated. In the final chapter, various policy recommendations were developed based on the findings obtained.

2. Theoretical framework

The banking sector is one of the industries where digital transformation is experienced the fastest due to technological developments. Mobile banking, internet branches, digital payment systems, and remote customer acquisition applications have transformed the traditional service model of banking; this transformation has had various effects on bank profitability (Ozili 2018). In this context, the impact of digitalization on bank performance can be evaluated under multiple theoretical frameworks. According to the efficiency theory, the integration of digital technologies into banking processes reduces transaction costs and increases operational efficiency (Berger and Mester 2003). Digital channels such as mobile banking and internet branches reduce the need for physical branches, lowering fixed costs while providing faster service to more customers. This can positively impact bank profitability through an increase in revenue per unit cost. The diffusion of innovations theory developed by Rogers (2003) suggests that the adoption process of digital technologies varies over time among banks. Early digitalizing banks can experience an increase in profitability by gaining a competitive advantage through higher customer satisfaction and transaction volume. In this context, digitalization is a factor that supports bank performance in terms of both market access and service quality. Banks are financial institutions that serve as intermediaries between savers and investors. The execution of this function in a digital environment accelerates processes such as the evaluation of loan applications and the automation of customer risk scoring (Allen and Santomero 1997). Thus, the bank can increase its credit revenues by serving a wider customer base at a lower cost. The resource-based approach proposed by Barney (1991) suggests that digital infrastructure creates a strategic competitive advantage for banks. In this approach, digital technologies are seen as rare, difficult to imitate, and firm-specific resources. The digital capabilities possessed by the bank support the sustainability of long-term profitability by increasing customer satisfaction. Although digitalization investments require significant capital in the initial phase, in the medium and long term, the benefits provided by these investments outweigh the costs (Bălăcescu 2021). Especially the low-cost products, cross-selling opportunities, and customer loyalty offered through digitalization strengthen the return on investment by increasing bank revenues. Behavioral finance approaches suggest that digital channels influence customer behaviors and create more frequent, faster, and personalized interactions between the bank and the customer (Thaler 2000). This process contributes to the diversification of bank revenues by increasing customer loyalty and transaction volume. Digitalization has many direct and indirect impacts on bank profitability. These effects can occur in both directions, reducing costs and increasing revenues. These theoretical approaches demonstrate that digitalization is not only a technological transformation for banks but also a strategic and financial leverage.

Türkiye is one of the countries that performs highly in the field of digitalization. The close relationship of the young population with technology also facilitates the development of this field. In recent years, digital banks operating without branches have entered the sector, with a total of 5 banks obtaining digital licenses: Colendi Bank A.Ş., Fubs Bank A.Ş., and Ziraat Dinamik Banka A.Ş. in the area of deposit banking; and Hayat Finans Katılım Bankası A.Ş. and T.O.M. Katılım Bankası A.Ş. in the area of participation banking (www.bddk.org.tr). In general, it will be evaluated whether the reflection of the impact of the increase in digital banking and transaction volume on bank performance is in line with expectations. Additionally, whether there is a distinction between deposit banks and participation banks in this regard will be addressed. To highlight the effects of the increasing digitalization after the pandemic on a sectoral basis, the study has been addressed with current data.

2.1. Theoretical foundations of profitability-based performance analysis in banks

There are five fundamental criteria for profitability. These are profit margin, net interest margin, spread, return on assets, and return on equity. The profit margin is calculated as follows (Saunders et al. 2019; Mishkin and Eakins 2018).

$$Profit\ Margin = \frac{Net\ income}{Total\ Income} \tag{1}$$

Bank managements aim to maximize shareholder returns in the long term. In this context, just like in other business management practices, the primary goal is to increase profitability. In line with this objective, bank managements focus on effectively managing interest expenses, which are one of the key components of resource costs. In this context, the analysis of the interest margin serves as an important indicator of the financial performance of banking activities.

Net interest margin (NIM) can be calculated by dividing the difference between interest incomes and interest expenses by earning assets (Saunders et al. 2019).

$$Net\ Interest\ Margin\ = \frac{(Interest\ Income - Interest\ Expenses)}{Earning\ Assets} \tag{2}$$

In asset-liability management practices, net interest income (NII) is an important performance indicator; however, in interbank comparisons, net interest margin (NIM) comes to the forefront. Net interest margin is obtained by relating the difference between interest income and interest expenses to earning assets, and therefore, in some studies, it is also referred to as "spread management" (Saunders et al. 2019; Rose and Hudgins 2013; Akgüç 2012).

The spread is one of the fundamental profitability indicators widely used in the banking sector and is closely related to the net interest margin (NIM). Both indicators measure the banks' capacity to generate interest-based income, but there is a technical difference between them. The net interest margin is obtained by relating net interest income to interest-earning assets, while the interest spread is defined as the difference between the ratio of interest income to interest-earning assets and the ratio of interest expenses to interest-bearing liabilities. Therefore, the interest rate spread reflects the bank's management of interest rates on both assets and liabilities and is a more analytical performance measurement tool compared to the net interest margin (Bikker and Vervliet 2022; Dietrich and Wanzenried 2011; Yaldız Hanedar 2020).

The return on assets (ROA) of banks generally remains at lower levels compared to companies operating in the industrial and service sectors. The main reason for this is that banking activities are subject to high leverage ratios and regulatory constraints.

$$Return\ on\ Assets(ROA) = \frac{Net\ Income}{Total\ Assets} \tag{3}$$

Additionally, ROA ratios vary according to the scale of the banks. Small-scale banks can achieve higher ROA values compared to large-scale banks during certain periods, but changes in market conditions can reverse this situation (Dietrich and Wanzenried 2011; Bikker and Vervliet 2022). However, the return on equity (ROE) is of strategic importance as it measures the bank's profitability from the shareholder's perspective and should be evaluated alongside the ROA ratio (Petria et al. 2015).

$$Return\ on\ Equity(ROE) = \frac{Net\ Income}{Total\ Equity} \tag{4}$$

The different profitability metrics used by banks reflect various aspects of the business's financial performance. The profit margin indicates how much profit the bank earns from every 1 TL of transaction income, while return on assets (ROA) and return on equity (ROE) represent the return rates derived from the bank's total assets and shareholders' investments, respectively. ROA measures how efficiently the bank uses its total assets, while ROE indicates the return on investors' capital and evaluates profitability from the shareholders' perspective (Dietrich and Wanzenried 2011; Bikker and Vervliet 2022).

3. Literature

The effects of digitalization on the banking sector have been intensively researched in recent years, particularly the reflections of digital banking on bank performance, which have attracted the attention of academic and sectoral circles. In the literature, it is frequently emphasized that digital banking increases operational efficiency, reduces costs, and thereby positively affects bank profitability (Boukhatem and Ben Moussa 2018; Ozili 2018). In Türkiye, digital banking applications gained momentum especially in the second half of the 2010s; with the widespread adoption of technological developments such as mobile banking, internet branches, and remote customer acquisition, customer behaviors and banking processes have been reshaped (TBB 2024). The Turkish banking sector has reached a level comparable to OECD countries in terms of digitalization; the number of transactions conducted through digital channels has come to constitute the vast majority of total transactions.

Empirical studies examining the impact of digital banking on bank performance have yielded different results for banks in Türkiye. Ulusoy and Demirel (2022) found a positive continuity between digitalization and profitability in their analysis of banks in Türkiye. Similarly, İslamoğlu and Bayraklı (2022) observed that the digital banking services offered by banks in Türkiye have positive effects on the financial performance of the banks. The literature on participation banking, on the other hand, evaluates the effects of digitalization within the framework of both technological capacity and religious and ethical principles. It has been observed that participation banks operating in Türkiye have progressed more cautiously in their digital transformation processes compared to conventional banks; however, this gap has been decreasing in recent years (Can and İslamoğlu 2023). Ahmetoğulları (2023) have shown that the impact of the digitalization level of participation banks on profitability is lower but positive compared to deposit banks. This situation can be explained by differences in product diversity and customer base.

Bekaroğlu (2024) state that digital banking applications significantly enhance customer experience. Canbaz and Erbaş (2021) stated that participation banks encountered certain structural difficulties during the integration process of FinTech applications. Doğan (2024) states that digitalization has positive effects on the efficiency of participation banks in Türkiye.

Theiri and Alareeni (2023) examined the impact of digital transformation on financial performance in public banks in Tunisia. The results indicate that digital transformation has a positive impact on Return on Assets (ROA) and Return on Equity (ROE). These findings indicate that digitalization is a significant factor in increasing the profitability of banks. Citterio et al. (2024) this research examined the impact of digital transformation on profitability in banks in Central and Eastern European countries. The results indicate that digital transformation has a positive impact on Return on Assets (ROA) and Return on Equity (ROE). This study emphasizes that digitalization is an effective tool for improving the financial performance of banks.

Zhu and Jin (2023) this study examined the impact of digital banking transformation on the operational capabilities of commercial banks. The results show that digital transformation enhances operational capabilities, but COVID-19 negatively impacts this relationship. These findings indicate that digitalization plays a significant role in increasing the operational efficiency of banks, but external factors can also be influential in this process. Shanti et al. (2023) examined the impact of digital transformation on profitability in seven banks in Indonesia. The results show a U-shaped relationship between digital transformation and profitability, meaning that digital transformation can initially decrease profitability but create positive effects in the long run. According to Rabbani et al. (2021), the digital transformation process is increasing the competitiveness of participation banks. According to Amin (2016), the transition to internet banking in Islamic banks is closely related to user behaviors.

Kammer et al. (2015) emphasized that the Islamic finance sector has been slow to seize digitalization opportunities.

Overall, the results obtained from the studies indicate that, in line with theoretical expectations, the impact of digitalization on operational efficiency and cost reduction is positive. Additionally, the impact of digitalization on bank profitability can vary seasonally due to the effects of macroeconomic uncertainties and regulatory changes. For example, while the COVID-19 pandemic increased the demand for digital banking services, the simultaneous rise in credit risks and operational costs affected bank performances in different ways (BDDK 2022). All these findings reveal that the impact of bank digitalization on financial performance in Türkiye varies both over time and by type of bank. Therefore, it is expected that comparative analyses conducted with a distinction between participation and deposit banks will fill the gaps in the literature and guide policymakers.

4. Method

4.1. Data set

In the study, data from participation banks and deposit banks were used to conduct the Toda-Yamamoto causality test on the developments related to digitalization and the impact of external data on bank performance during the period from 2010 to 2024. The ROA of Participation Banks is shown in Figure 1, and the ROA of Deposit Banks is shown in Figure 2.

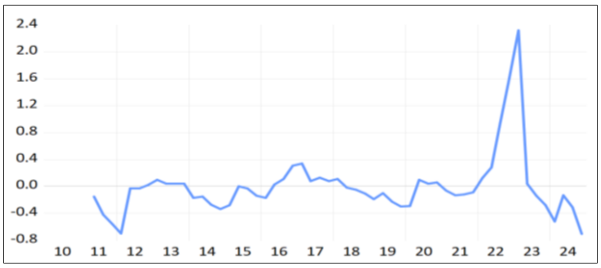

Figure 1. Deposit Banks ROA

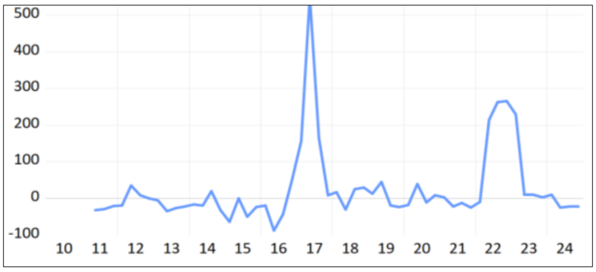

Figure 2. Participation Banks ROA

In this study, the effects of digitalization and macroeconomic variables on bank profitability were analyzed using data from deposit and participation banks operating in Türkiye. The dataset covers the period from 2010 to 2024 and includes a total of 59 observations collected on a quarterly basis. The variables used in the research are classified into the following two groups:

- Bank performance variables:

- For deposit banks, active return on assets (MROA) and non-performing loans ratio (MT)
- For participation banks, active return on assets (KROA) and non-performing loans ratio (KT)

- Digitalization and macroeconomic control variables:

- Number of digital banking customers (data from the Turkish Banks Association and BDDK)
- TCMB policy interest rate
- Annual inflation rate based on CPI
- Türkiye's five-year country risk premium (CDS spread, basis points)

Micro data on bank performance has been obtained from sectoral reports published by the BDDK and TBB. Macroeconomic data, on the other hand, has been obtained from reliable sources such as the Central Bank of the Republic of Türkiye's Electronic Data Distribution System (EVDS), Bloomberg, and Trading Economics. The digital banking customer count (DBMS) variable has been used to represent the level of digitization in the banking system. This variable encompasses the total number of internet banking and mobile banking users. The frequency of the data has been determined as quarterly to be suitable for both panel data and time series analysis. In this way, both short-term changes and long-term trends have been included in the analysis. The details of the variables used in the study are presented in Table 1.

Table 1. Variables used in the study

Abbreviation	Variable Name	Description
MROA	Deposit Banks' Return on Assets Ratio	Deposit banks' profitability ratio based on periodic total assets
MT	Deposit Banks' Non-Performing Loan Ratio	The ratio of non-performing loans to total loans in deposit banks
CDS	Türkiye's Risk Premium	The 5-year CDS score reflecting country risk (basis points)
INF	Inflation	The rate of increase in the consumer price index (CPI) over the previous month
RATE	Policy Rate	The short-term policy rate determined by the Central Bank of the Republic of Türkiye (CBRT)
DBMS	Number of Digital Banking Customers	The number of customers using digital services in the banking system
KROA	Participation Banks' Return on Assets Ratio	The profitability ratio of participation banks' profitability ratio based on periodic total assets
KT	Participation Banks' Non-Performing Loan Ratio	The ratio of non-performing loans to total loans in participation banks

Descriptive statistics for the variables are presented in Table 2. The dataset consists of 14 years of data. The average values in Table 2 represent quarterly rates of change over the specified time period. The delinquency rates of participation banks and deposit banks are observed to be similar.

Table 2. Descriptive statistics

	KROA	KT	RATE	INF	CDS	DBMS	MROA	MT
Mean	0.802881	3.535254	12.82525	1.552542	30639.86	42.00190	0.971017	3.276271
Maximum	3.070000	6.950000	50.00000	7.780000	78413.00	117.3020	3.420000	5.600000
Minimum	0.020000	0.980000	4.500000	-0.110000	13739.00	6.006000	0.150000	1.640000
Standard Deviation	0.650403	1.324563	10.64088	1.703804	14734.63	35.29628	0.672147	0.945034
Jarque-Bera	35.12414	0.195874	109.2575	85.94997	17.55055	7.166482	32.14074	2.832786
Probability	0.000000	0.906706	0.000000	0.000000	0.000155	0.027785	0.000000	0.002587
Observation	59	59	59	59	59	59	59	59

4.2. Research model

An empirical model is proposed to analyze the impact of digitalization and macroeconomic variables on the profitability of deposit and participation banks operating in Türkiye. The dependent variables used in the research are MROA (Return on Assets Ratio of Deposit Banks) for deposit banks and KROA (Return on Assets Ratio of Participation Banks) for participation banks. The independent variables consist of DBMS (Number of Digital Banking Customers) as a proxy for digitalization, non-performing loan ratios (MT and KT) representing the bank's risk structure, and CDS (country risk premium), INF (inflation), and RATE (policy rate) variables reflecting the macroeconomic environment. The research model is constructed separately for bank types and expressed according to the following structural form:

$$\begin{aligned} MROA_t = \alpha_0 &+ \sum_{i=1}^{5} \beta_{1i} MROA_{t-i} + \sum_{i=1}^{5} \beta_{2i} DBMS_{t-i} + \sum_{i=1}^{5} \beta_{3i} RATE_{t-i} + \sum_{i=1}^{5} \beta_{4i} CDS_{t-i} \\ &+ \sum_{i=1}^{5} \beta_{5i} INF_{t-i} + \sum_{i=1}^{5} \beta_{6i} MT_{t-i} + \gamma_{16} MROA_{t-6} + \gamma_{26} DBMS_{t-6} + \gamma_{36} RATE_{t-6} \\ &+ \gamma_{46} CDS_{t-6} + \gamma_{56} INF_{t-6} + \gamma_{66} MT_{t-6} + \epsilon_{it} \end{aligned} \tag{5}$$

The model equation established for participation banks is stated in (6).

$$KROA_t = \alpha_0 + \sum_{i=1}^{5} \beta_{1i} KROA_{t-i} + \sum_{i=1}^{5} \beta_{2i} DBMS_{t-i} + \sum_{i=1}^{5} \beta_{3i} FA\dot{I}Z_{t-i} + \sum_{i=1}^{5} \beta_{4i} CDS_{t-i} + \sum_{i=1}^{5} \beta_{5i} INF_{t-i} + \sum_{i=1}^{5} \beta_{6i} KT_{t-i} + \gamma_{16} KROA_{t-6} + \gamma_{26} DBMS_{t-6} + \gamma_{36} RATE_{t-6} + \gamma_{46} CDS_{t-6} + \gamma_{56} INF_{t-6} + \gamma_{66} KT_{t-6} + \epsilon_{it} \quad (6)$$

4.3. Data analysis

In econometric analyses, it is necessary for the time series used to be stationary in order to obtain meaningful and reliable results. Stationarity is the condition where the mean and variance of a time series remain constant over time, and the joint variance between two periods is influenced not by their absolute time but only by the distance (lag) between them. Such processes are considered to have statistical properties that do not change over time probabilistically (Gujarati 2003).

Table 3. Unit root test results

Variables	ADF		Phillips Perron		GLS	
	Constant t-ist.	Constant and Trending t-ist.	Constant t-ist.	Constant and Trending t-ist.	Constant t-ist.	Constant and Trending t-ist.
MROA	0.0677*	0.1591	0.0000***	0.0000***	-2.447313**	-3.044637*
MT	0.1332	0.3489	0.2450	0.5445	-1.571217	-2.229315
CDS	0.3501	0.1778	0.2895	0.3590	-1.657603	-2.930165*
INF	0.0091***	0.0004***	0.0160**	0.0003***	-3.609237***	-4.878584***
RATE	0.1055	0.0045***	0.9772	0.8787	-2.657547	-4.135283***
DBMS	0.8980	0.9620	0.9761	0.9615	-0.004661	-0.351160
KROA	0.4485	0.5515	0.0001***	0.0002***	-1.506651	-2.253859
KT	0.6825	0.7928	0.6567	0.7666	-0.880452	-1.673935
ΔMROA	0.0262**	0.0075***	0.0000***	0.0001***	-0.697401***	-1.990963***
ΔMT	0.0206**	0.0064***	0.0225**	0.0045***	-2.317830**	-2.887642**
ΔCDS	0.0000***	0.0000***	0.0000****	0.000****	-6.470543***	-5.506848***
ΔRATE	0.0004***	0.0015***	0.0167**	0.0058***	-6.594260***	-5.861613***
ΔDBMS	0.0018***	0.0000***	0.0015***	0.0000***	-5.567899***	-4.538525***
ΔKROA	0.0157**	0.0480**	0.0000***	0.0000***	-5.881946***	-4.009218***
ΔKT	0.0000***	0.0000***	0.0000***	0.0000***	-7.157288***	-4.205668***

Note: The appropriate lag length for the ADF and GLS tests was determined using the Schwarz Information Criterion (max 3); the bandwidth for the PP test was determined using the Newey-West Bandwidth Criterion. The GLS test statistic for the fixed model at the 1%, 5%, and 10% significance levels are -2.606163, -1.946654, and -1.61312, respectively. For the fixed and trend model, the values at the 1%, 5%, and 10% significance levels are -3.7434, -3.1676, and -2.8690, respectively. The values shown in parentheses are probability values. The *** symbol indicates a significance level of 1%, the ** symbol indicates a significance level of 5%, and the * symbol indicates a significance level of 10%.

In the study, ADF (Augmented Dickey-Fuller), Phillips-Perron (PP), and GLS (DF-GLS) tests were applied to determine the stationarity levels of the time series variables. The results of these tests are presented in Table 3. In all three tests, both stationary and stationary + trend models were used for the analysis. The test results are summarized below: In the level tests, only the INF (inflation) variable was found to be statistically significant in all tests, leading to the conclusion that it is stationary (I(0)). Additionally, the RATE and MROA variables appear to be stationary at the 10% significance level according to the DF-GLS test, especially in the trend model. The other variables, MT, CDS, DBMS, KROA, KT, are not stationary at level; this indicates that these series contain a unit root and using them without differencing could be misleading. As a result of the tests applied to the first-differenced series

(Δ), it was observed that all variables became stationary at the 1% or 5% significance level (I(1)). This situation indicates that the variables are integrated of order one. In summary, although most of the series are not stationary at the level, stationarity has been achieved when their first differences are taken. Therefore, it has been appropriate to prefer methods that take into account the integration degrees of the series, such as the Toda-Yamamoto causality test. The test results allowed for the transition to causality analysis without examining whether there is a cointegration relationship between the series.

Table 4. Autocorrelation LM test results

Delay	LM Statistic	Prob.
0	60.20059	0.0969
1	50.02093	0.0602
2	52.21129	0.0894
3	46.53010	0.1124
4	54.22536	0.0761
5	70.67740	0.0605

According to the results in Table 4, statistically significant autocorrelation was not detected in most lags in the residuals ($p > 0.05$). These results indicate that, in general, the residuals of the VAR model do not exhibit serial dependence and that the model is suitable for the Toda-Yamamoto application. Although a value close to the threshold was obtained in a single lag, it is assessed that the overall structure of the model is robust and the reliability of the findings is not compromised.

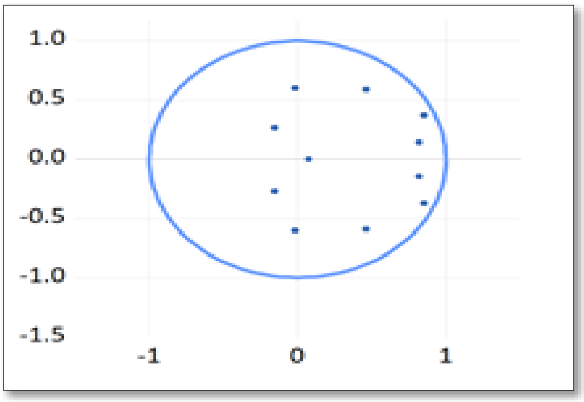

Figure 3. Inverse roots of AR characteristic polynomials for deposit banks

To test whether the applied VAR model is stationary, the distribution of the characteristic roots has been examined. As shown in Figure 3, it has been observed that all the roots lie within the unit circle. This finding indicates that the model satisfies the stationarity condition and is therefore suitable for transitioning to the Toda-Yamamoto causality analysis.

Table 5. Appropriate delay length for deposit banks ROA

Delay	LogL	LR	FPE	AIC	SC	HQ
0	-1216.614	NA	1.874512	45.28201	45.50301	45.36724
1	-861.0970	618.8634	13654437	33.44804	34.99502	34.04465
2	-796.2111	98.53038	4919713	32.37819	35.25117	33.48618
3	-755.4584	52.82757	4701285	32.20216	36.40113	33.82154
4	-658.5006	104.1398	643426	29.94447	35.46942	32.07523
5	-588.6528	**59.49998***	**301835.4***	**28.69085***	35.54179	**31.33299***

Note: * indicates lag order selected by the criterion. LR: Sequential modified LR test statistics, FPE: Final prediction error, AIC: Akakike information criterion, SC: Schwarz information criterion, HQ: Hannan-Quinn information criterion

In order to determine the number of lags to be used in the Toda-Yamamoto causality analysis, the information criteria of the VAR model were evaluated, and the results are presented in Table 5.

According to the results of AIC, FPE and LR, the most suitable number of lags was determined to be 5. Although more penalizing criteria like SC (Schwarz Criterion) and HQ (Hannan-Quinn) suggest lower lag levels, the number of lags was chosen as 5 (m=5) based on the AIC criterion to maximize the model's forecasting power. This value was used to create the VAR(6) model by adding the integration degree of the series (d_{max}=1), and the Toda-Yamamoto approach was applied.

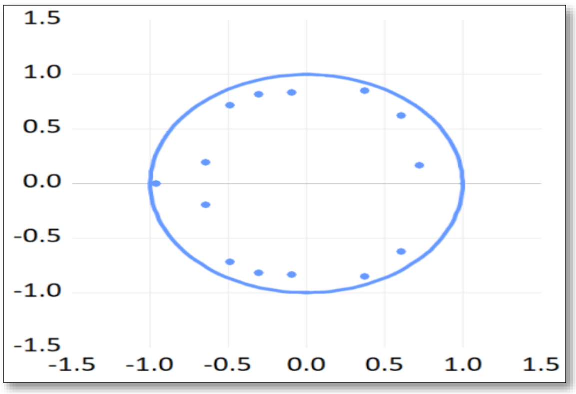

Figure 4. Inverse roots of AR characteristic polynomials for participating banks

By setting the lag number to 5, it is understood from the Figure 3 and Figure 4 below that the estimated VAR models are stationary, as all the roots of the AR characteristic polynomial lie within the unit circle.

Table 6. Appropriate lag length for participation banks ROA

Delay	LogL	LR	FPE	AIC	SC	HQ
0	-1221.089	NA	2.2045212	45.44773	45.66873	45.53296
1	-918.4308	526.8489	1.1442208	35.57151	37.11850	36.16812
2	-877.4236	62.27019	99596008	35.38606	38.25904	36.49406
3	-823.2191	70.26510	57829144	34.71182	38.91079	36.33120
4	-749.1663	79.53820	18486488	33.30246	38.82741	35.43322
5	-697.3455	44.14368	**16907883***	**32.71650***	39.56744	**35.35864***

Note: * indicates lag order selected by the criterion. LR: Sequential modified LR test statistics, FPE: Final prediction error, AIC: Akakike information criterion, SC: Schwarz information criterion, HQ: Hannan-Quinn information criterion

In the VAR model established to determine the number of lags to be used in the Toda-Yamamoto causality analysis for participation banks, information criteria were evaluated. According to the criteria AIC, FPE and HQ in Table 6, the optimal lag order was determined to be 5. In this context, the Toda-Yamamoto method was applied by estimating the VAR(6) model along with the degree of integration of the series.

5. Findings

The most commonly used method to test the causal relationship in time series analyses is the Granger causality test developed by Granger (1969). This test examines the contribution of the past values of one variable in predicting the current values of another variable. However, the Granger test can only be applied to stationary series, and the stationarization of the series may lead to information loss (Nazlıoğlu et al. 2016). Additionally, if there is a cointegration relationship between the series, the F-statistic of the Granger test may lose its standard distribution properties.

To address these limitations, Toda and Yamamoto (1995) developed a method that works with level values regardless of the stationarity degree or cointegration relationship of the series and allows for causality analysis using the Wald test. The Toda-Yamamoto causality test is conducted on the VAR(k+dmax) model, which is formed by adding dmax lags to the VAR model after determining the maximum integration order (dmax) of the series. In this model, the causality relationship is investigated by testing significance with the Wald test (Eita and Jordaan 2007). In this respect, the Toda-Yamamoto approach is a flexible method that allows for causality analysis with integrated series of different orders (Toda and Yamamoto 1995). For the Toda-Yamamoto causality test of variables Y and X, the estimated VAR (k+d_{max}) model is as follows.

$$Y_t = \omega + \sum_{i=1}^{k} \alpha_{1i} X_{t-i} + \sum_{i=1}^{k} \beta_{1i} Y_{t-i} + \sum_{j=k+1}^{d_{max}} \delta_{1i} X_{t-i} + \sum_{j=k+1}^{d_{max}} \theta_{1i} Y_{t-i} + \varepsilon_{1t} \quad (7)$$

$$X_t = \varphi + \sum_{i=1}^{k} \alpha_{2i} X_{t-i} + \sum_{i=1}^{k} \beta_{2i} Y_{t-i} + \sum_{j=k+1}^{d_{max}} \delta_{2i} X_{t-i} + \sum_{j=k+1}^{d_{max}} \theta_{2i} Y_{t-i} + \varepsilon_{2t} \quad (8)$$

H_0: There is no causal relationship from variable Y to variable X.
H_1: There is a causal relationship from variable Y to variable X.

To determine the existence of a mutual causality relationship between the variables, the hypotheses H_0: α_{1i}=0 and H_0: α_{2i}=0, which express whether the coefficients are equal to zero, are tested using the modified WALD test statistic. If the modified WALD test statistic is greater than the k degrees of freedom value in the X^2 table, these hypotheses are rejected (Toda and Yamamoto 1995).

Table 7. Results of Granger causality test applied with the Toda-Yamamoto method

Direction of Causality	Chi-Square Test	Probility	Decision
MT → MROA	31.08322	9,0194	No evidence of causality was found.
CDS →MROA	55.19255	1,1915	No evidence of causality was found.
INF →MROA	242.8591	1,3759	No evidence of causality was found.
RATE→MROA	23.47319	**0,0006**	There is a causal relationship between the variables.
DBMS→MROA	13.58352	**0,0346**	There is a causal relationship between the variables.
KT → KROA	16.48161	**0,0055**	There is a causal relationship between the variables.
CDS → KROA	14.70524	**0,0053**	There is a causal relationship between the variables.
INF → KROA	92.29099	1,0123	No evidence of causality was found.
RATE→ KROA	15.45042	0,0170	There is a causal relationship between the variables.
DBMS→ KROA	10.44299	0,1071	No evidence of causality was found.

Note: Delay Length m=5 d_{max}=1 (m+ d_{max}=6)

In the study, the causality relationship between digitalization and bank profitability was examined using quarterly data from 2010 to 2024 for deposit and participation banks operating in Türkiye, employing the Toda-Yamamoto causality test. Within the scope of the analysis, the banks' active profitability (MROA and KROA) was taken as the dependent variable; the impact of the variables representing the level of digitalization and the macroeconomic control variables on these indicators was evaluated.

In the applied Toda-Yamamoto test, a VAR(6) model was created considering the maximum integration order of the series (d_{max}=1) and the lag length (m=5). The findings in Table 7 can be summarised as follows: In terms of the return on assets (MROA) of deposit banks, it has been observed that there is a significant causal relationship between the interest rate (RATE) and the level of digital banking usage (DBMS) ($p < 0.05$). This finding indicates that the effective use of interest policies and digital channels is decisive for the profitability of deposit banks. In terms of the active profitability of participation banks (ROAA), it has been determined that the variables of participation transaction intensity (PT), country risk premium (CDS), and interest rate (IR) carry significant causality ($p < 0.05$). Considering that participation banks adopt non-interest income models compared to traditional banks, this result is significant as it indicates that participation banks are more sensitive to macroeconomic fluctuations. Inflation (INF) and some other control variables, while producing significant results in some models, do not present a consistent causal relationship. The lack of statistically significant impact of the CDS premium on deposit banks suggests that traditional banking is relatively more resilient to international market risks. On the other hand, the significant causality of the same variable on participation banks suggests that interest-free financial institutions may have a higher sensitivity to international risks.

In conclusion, it is observed that the impact of digitalization on banking profitability varies according to the type of bank. In deposit banks, it is understood that digitalization is a strong tool in terms of efficiency and income generation; whereas in participation banks, the impact of digitalization is more shaped by external macroeconomic conditions.

6. Conclusion and discussion

This study investigated the causal relationships between digitalization, macroeconomic variables, and bank profitability for participation and deposit banks in Türkiye during the 2010–2024 period, employing the Toda-Yamamoto causality approach. The findings highlight notable structural differences between the two banking models and indicate that the effects of digitalization on profitability are neither uniform nor independent of macroeconomic conditions.

Interest rates for deposit banks and digital banking activities have a significant causal impact on asset returns. These findings are consistent with the broader literature on digital banking and bank performance. Previous studies, particularly in traditional banking systems, emphasize that digitalization improves profitability by increasing operational efficiency and customer experience (Boukhatem and Ben Moussa 2018; Ozili 2018; Ulusoy and Demirel 2022). The literature on participation banking emphasizes that the speed and scope of digital transformation are often limited by product specificity, regulatory considerations, and compliance with Islamic finance principles. This situation can reduce the impact of digitalization on financial performance (Can and İslamoğlu 2023; Ahmetoğulları 2023; Rabbani et al. 2021; Canbaz and Erbaş 2021). This contextualization strengthens the observed heterogeneity in the effects of digitalization among bank types in Türkiye by placing the study's findings within the existing research. These findings indicate that technology-driven efficiency gains, when combined with effective interest rate management, directly improve financial performance in traditional banking systems. The strong link between the adoption of digital services and profitability in deposit banks can be attributed to their established technological infrastructure. This infrastructure enables them to reach broader customer bases, diversify their product portfolios, and scale digital investments more effectively.

For participation banks, profitability is significantly influenced by the ratio of non-performing loans to total loans in participation banks variable, representing the intensity of specific participation-based transaction types, and by country risk as measured through CDS premiums. The heightened sensitivity to sovereign risk mirrors the observations of Hassan et al. (2013), who note that interest-free financial institutions often face higher exposure to macroeconomic volatility due to their limited hedging instruments and more concentrated revenue streams. The product-specific nature of digitalization in participation banks suggests that their digital strategies are still in a formative stage, focusing on niche services rather than fully integrated digital ecosystems.

The divergence in findings between bank types may stem from differences in business models, regulatory requirements, capital structures, and target customer segments. Additionally, macroeconomic instability in Türkiye particularly during the post-pandemic period appears to have amplified these differences, with deposit banks leveraging their scale to absorb shocks more effectively, while participation banks remain more vulnerable to external risks.

For both bank types, digital investments should not be limited to customer acquisition tools but integrated into long-term operational strategies aimed at process automation, cost reduction, and new revenue channels. To reduce vulnerability to macroeconomic fluctuations, participation banks should diversify their digital product offerings, moving beyond a narrow concentration on specific transaction types. Policymakers should maintain an adaptive regulatory environment that encourages technological innovation while ensuring financial stability. This includes only facilitating the entry of digital banks and supporting interoperability between digital platforms. The shift toward digitalization requires banks to invest in developing digital skills for their employes, integrate data analysis into decision-making processes, and restructure human resources policies to support flexible, technology-focused work processes. Targeted human resources strategies for participation banks can focus on recruiting talent that is both knowledgeable in Islamic finance and has expertise in digital technologies.

By combining technological, regulatory, and human capital strategies, the banking sector can maximize the efficiency and resilience gains from digitalization while mitigating its uneven effects across bank types. The study contributes to the literature by providing a comparative, macro-contextualized analysis of digitalization's impact on profitability and offers a set of actionable recommendations for policymakers, bank executives, and HR managers seeking to navigate the ongoing digital transformation.

Declaration of competing interest

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

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Towards sustainable digital futures in banking: Insights from science mapping techniques

Asuman ERBEN YAVUZ[1]

HIGHLIGHTS

[1] Baskent University, Vocational School of Social Sciences, Ankara, Türkiye, asumanerbenyavuz@gmail.com

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ABSTRACT

This study aims to examine scientific studies on digitalization in banking in terms of bibliometric indicators. In this context, the publications in the Scopus database were scanned and 887 studies were reached. The obtained studies were subjected to bibliometric analysis with the science mapping technique and classified according to the topics and contents identified in the relevant literature. The results of the research show that the first article on digital finance was published in 2010 and that there was a very limited number of studies on the subject until 2017. The year 2024 was the year with the highest number of publications on the subject. Studies were published in 105 countries, with India being the country with the highest number of publications and citations on digitalization in banking. Recent studies have focused on cyber security, artificial intelligence, sustainable banking, digital inclusive finance, energy efficiency and technological development.

1. Introduction

Information technologies are transforming the structure of industrial competition and the value proposition offered to customers on a global scale, and the banking sector is directly affected by this transformation. Indeed, digitalization accelerates the emergence of innovative business models that change the structure of the financial system, leading to radical transformations in the sector (Shaikh et al. 2020; Rahi et al. 2021). The increasing presence of fintech companies and the provision of personalized, fast and secure services to customers through digital financial solutions have created serious competitive pressure on traditional banking models (Wewege et al. 2020; Phan et al. 2020). In this context, banks have focused on increasing operational efficiency and improving customer experience by integrating digital technologies into their business models. Innovative services such as real-time payment systems, online loan applications and mobile banking platforms have become widespread in the financial system, offering digital alternatives to traditional banking products (Shaikh et al. 2020; Allen et al. 2022). Especially with the proliferation of internet and mobile-based platforms, it has become possible for users to perform their banking transactions without time and space restrictions (Wewege et al. 2020; Rahi et al. 2021).

The digital transformation process of the banking sector requires a high level of IT (information technology) investment, and the cost-effectiveness of these investments should be carefully evaluated by managers (Kitsios et al. 2021). While digitalization offers banks cost advantages and competitiveness, it also brings multidimensional challenges such as regulatory risks, security threats and strategic alignment issues (Khattak et al. 2023; Miskam et al. 2019). Recent studies point to the positive effects of IT investments on bank profitability and reveal that technological adaptation creates competitive advantage (Del Gaudio et al. 2020; Le and Ngo 2020). However, for the digital finance ecosystem to thrive, it is important for governments to establish a regulatory framework that supports innovation and ensures data security (Tsindeliani et al. 2021). In this context, understanding the current state of digital banking in developing countries is crucial to determine the direction of academic knowledge production. In these countries, digital financial inclusion stands out as a strategic element for economic development and fintech solutions provide services to individuals and institutions that the traditional financial system cannot reach (Finkelstein-Shapiro et al. 2022).

The aim of this study is to examine the academic literature produced in the field of digital banking through bibliometric analysis and to determine the structural dynamics of this field. In this context, indicators such as publication volume, author influence, collaboration networks, thematic clusters and citation densities were analyzed. Visualizing the knowledge densities in the literature through thematic maps allows us to identify which topics are prominent in the adoption process of digital banking. The findings provide important contributions for universities, research centers and policy makers in terms of shaping collaboration strategies, identifying knowledge gaps and determining future academic directions (Dissanayake et al. 2023; Garg et al. 2023; Parker et al. 2023).

The rapid transformation of the financial sector through digitalization has created an urgent need to better understand the scope, direction, and thematic evolution of research in this field. Despite the growing relevance of digital finance, the existing body of literature lacks a comprehensive overview that systematically traces its intellectual development. This study is motivated by the necessity to close that gap by identifying how digitalization in banking has been studied, which themes dominate the discourse, and how research interest has evolved over time. By focusing on a large dataset from the Scopus database and employing bibliometric mapping techniques, the research seeks to provide clarity and structure to a fragmented body of knowledge, thereby offering a valuable resource for academics, practitioners, and policymakers. This study makes several noteworthy contributions to the literature. First, it provides the most up-to-date and extensive bibliometric analysis of digitalization in banking, covering 887 publications across 105 countries. By identifying key research clusters such as cybersecurity, artificial intelligence, sustainable banking, and digital financial inclusion, it highlights the thematic priorities that shape the field today. Second, it contextualizes the temporal dynamics of research output, showing the acceleration of interest particularly after 2017 and peaking in 2024, thereby uncovering the drivers of scholarly attention. Finally, the study not only maps the intellectual structure of the literature but also sets the agenda for future research by revealing emerging themes such as energy efficiency and technological development, thus guiding scholars and practitioners toward unexplored but promising areas.

2. Literature review

2.1. Digital banking and technological transformation

Digitalization has radically changed not only the product and service delivery channels in the banking sector, but also the competitive structure and the nature of customer relationships. While traditional banking services have been replaced by fast, low-cost and user-friendly digital platforms, this transformation has been made possible by the proliferation of information technology-based service infrastructures (Shaikh et al. 2020; Rahi et al. 2021). In particular, applications such as mobile banking, internet banking and open banking have expanded banks' customer reach and facilitated access to financial services (Wewege et al. 2020; Allen et al. 2022). During this digital transformation process, banks have increased their IT investments with the aim of both reducing service costs and increasing customer satisfaction. While Scott et al. (2017) and Kitsios et al. (2021) draw attention to the effects of banks' digitalization strategies on operational efficiency, Khattak et al. (2023) emphasize that this transformation involves technical and regulatory risks and investment decisions should be evaluated at a strategic level.

Le and Ngo (2020) revealed the positive impact of information technology adoption on bank profitability and presented empirical evidence supporting the role of digital products and services in improving financial performance. This transformation has not only been limited to technological infrastructure but has also brought along multidimensional topics such as customer behavior, security perception, and financial inclusion (Del Gaudio et al. 2020).

The adoption of digital banking in developing countries is often framed in terms of financial inclusion and digital inequality. The limited traditional banking infrastructure in these countries allows for faster diffusion of fintech-based solutions. Finkelstein-Shapiro et al. (2022) argue that as digital technologies make financial services more accessible, individuals and businesses that cannot be integrated into the financial system can be served. However, not only technological capabilities, but also the regulatory framework, user safety and digital literacy are critical for the expansion of digital banking. Tsindeliani et al. (2021) note that fintech companies have proliferated in many developing countries, but these technologies are only supported by effective regulatory mechanisms in some countries. This is one of the main reasons explaining regional development gaps.

2.2. Mapping the literature with bibliometric analysis

As the literature on digital banking expands, quantitative methods such as bibliometric analysis are becoming increasingly important for identifying research trends and mapping knowledge concentrations. Ren et al. (2020) stated that bibliometric analyses are effective in classifying dispersed knowledge clusters and revealing thematic relationships. Dissanayake et al. (2023) emphasize that such analyses are guiding both in identifying knowledge gaps and in identifying academic differences between countries.

Such analyses reveal the structural characteristics of the literature by examining not only the number of publications but also author collaborations, citation structures, keyword clusters and thematic orientations (Parker et al. 2023). It is also important to show which countries or institutions are leading the field and which topics are deepening in the literature (Garg et al. 2023).

In this framework, this study makes an original contribution by systematically examining the scholarly production in the field of digital banking through bibliometric analysis and visualizing academic clusters, collaboration networks and thematic concentrations in this field.

3. Method

In this study, bibliometric analysis method is used to reveal the structural characteristics and development dynamics of the academic literature on digitalization in banking. Bibliometric analysis is a method developed to examine scientific publications published in a specific research field with statistical criteria and to systematically map the knowledge density in this field. In the application of this method, the volume, orientation, impact and structural relationships of scientific production are analyzed at different levels (author, institution, country, journal, keyword, reference, etc.).

3.1. Data collection process

The data set of the study was created through the Scopus database, which offers a comprehensive content in the fields of social sciences, management, finance and technology. The key term "digital banking" was used in the database searches and appropriate publications were filtered. The results obtained were updated as of 2025, and a total of 887 academic studies were reached. The search was limited to articles, reviews and proceedings; book chapters, editorials and technical notes were excluded.

3.2. Analysis tool and implementation process

The collected data were analyzed with VOSviewer (version 1.6.x), a bibliometric science mapping software. VOSviewer allows the extraction of structural patterns of scientific fields thanks to its capacity to identify relationships between publications (citation, co-author, keyword co-occurrence, bibliographic matching). visualization

The following steps were followed within the scope of the analysis process:

- **Analysis of temporal publication trends**: By examining the change in the number of publications over the years, the course of the level of interest in the literature over time was determined.
- **Thematic field analysis**: The multidisciplinary nature of the research was revealed by evaluating the distribution of publications according to disciplines.
- **Productivity and impact analysis at country, author and institution level**: Countries, authors and institutions with the highest number of publications were identified and their citation impact was measured.
- **Source analysis**: The journals with the highest number of publications and the most cited journals were identified.
- **Keyword co-occurrence analysis**: Thematic clusters were formed by analyzing key terms that are frequently used together.
- **Bibliographic coupling**: Structural clusters in the literature were visualized through the common reference structures of publications.
- **Temporal visualization:** Time-based densities were assessed on keyword clusters and bibliographic match maps**.**

3.3. Method appropriateness and limitations

Bibliometric analysis using a scientific mapping approach is a powerful method for visualizing knowledge production and discovering trends in a broad and multidisciplinary field such as digitalization in banking. However, the study also has certain limitations. First of all, only the Scopus database was used as a basis and publications in other academic indexes (Google Scholar) were excluded. Furthermore, the analysis was conducted only at the level of number of citations, document type and keywords; content analysis was excluded from the scope of this study.

4. Findings

The first article on digital banking obtained from the Scopus database was published in 2010, indicating that there was a very limited number of studies on the subject until 2017. 2024 was the year with the highest number of publications on the subject. The publication of the studies analyzed within the scope of the study by year is presented in Figure 1. This analysis is important in terms of revealing the course of academic interest in a particular research area over time. Thus, temporal trends can be observed in terms of the periods in which increases or decreases in publication production are concentrated and how the mobility in the literature is shaped in certain years can be identified. Moreover, such an assessment also contributes to the identification of periods when interest in the research topic increases or stagnates.

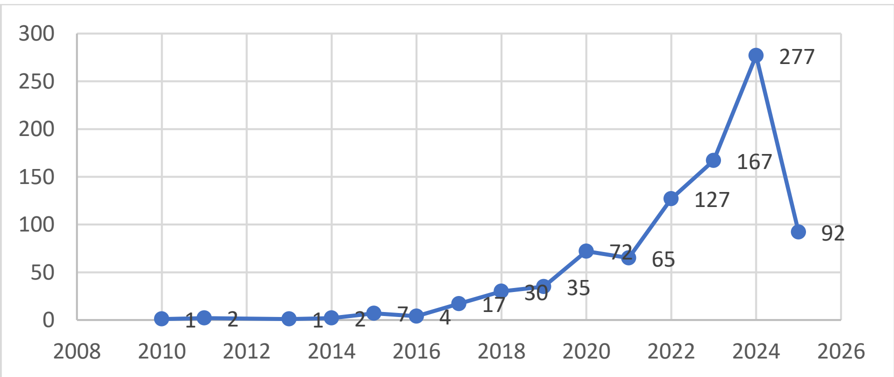

Figure 1. Distribution of digital banking studies by years based on data from Scopus

The banking sector, like other institutional structures, is facing structural transformation and disruptive innovation pressures driven by ever-evolving digital technologies. In this context, digitalization of service processes has become a strategic imperative for sectoral sustainability and competitive advantage. Considering the 2020-2023 period, there is a significant increase in the volume of academic publications on digital banking, and this trend reveals that digitalization is increasingly being researched at the academic level. Figure 2 confirms this, clearly reflecting an increase in scholarly interest in the adoption and research of digital banking.

Figure 2 shows the interdisciplinary distribution of the literature covered by the study. According to the results of the analysis, the most concentrated area of publications is Computer Science with 21%. This area is followed by the categories of Business, Management and Accounting and Other Fields with 18%. Taken together, these three fields account for 57% of the total publications and reveal that research is concentrated in digital technologies and management-based disciplines. In addition, the field of Economics, Econometrics and Finance stands out with 14%, supporting the economic analysis dimension of the study. Engineering (11%), Social Sciences (9%) and Decision Sciences (9%) stand out as disciplines that contribute to the technical, social and decision support systems aspects of the study. This distribution shows that the study is not limited to a specific discipline, but is shaped on a multidisciplinary research ground. This is important as it shows that the subject of the study has a broad theoretical and empirical base covering both technological and managerial dynamics.

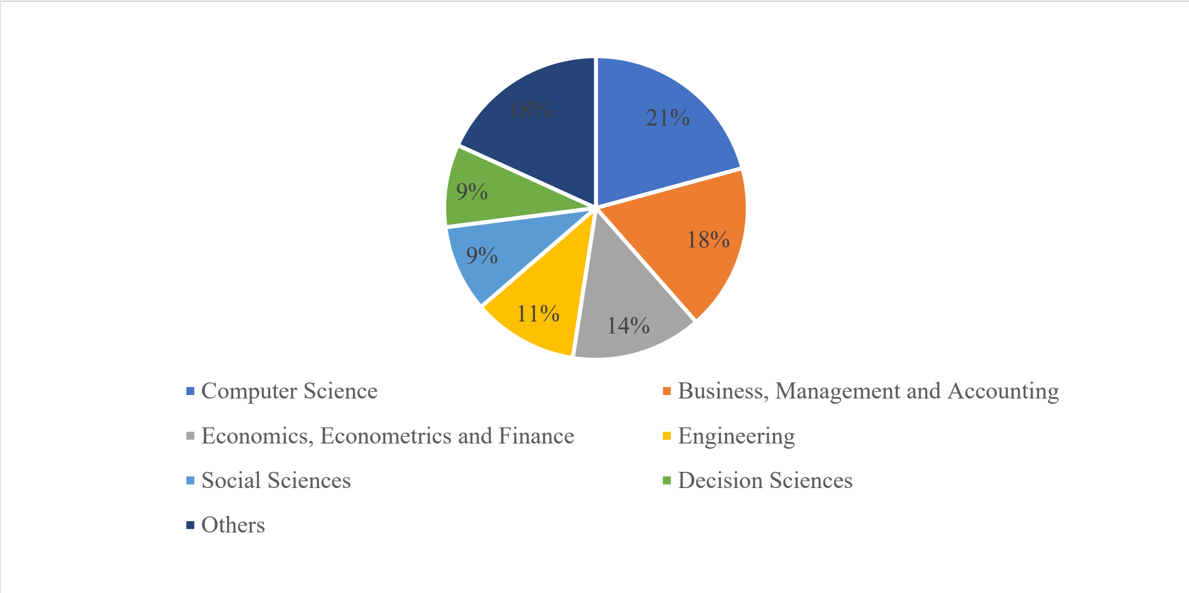

Figure 2. Thematic Areas Based on Data from Scopus

The geographical distribution of research outputs is a critical parameter for assessing the potential of international academic collaborations. Identifying the countries where scientific publications are produced enables the identification of geographical centers that stand out in knowledge production, as well as the analysis of structural differences between research capacities. Scientific productivity levels across countries are influenced by various factors such as infrastructure facilities, level of digitalization, thematic proximity and maturity of research ecosystems.

Figure 3 shows the distribution of publications in digital banking by country. According to the analysis, India is by far the country that produces the most scientific output. It is followed by Indonesia and the United Kingdom. On the other hand, countries such as the United States and China are represented by a more limited number of publications.

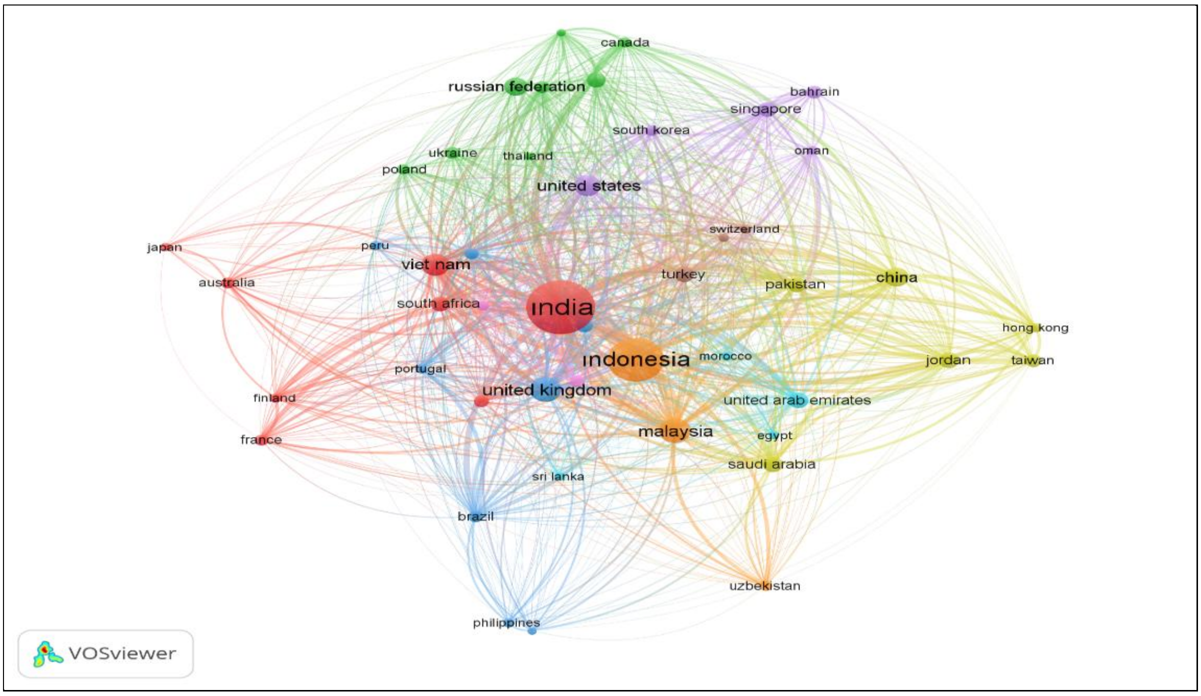

Figure 3. Network analysis by country

Table 1 also allows us to measure these countries by the citation power of the studies. It shows the distribution of academic production in the field of digital banking by country. In the analysis of 105 countries, India ranks first in terms of both the number of publications and the level of citations, representing a significant portion of global academic production in this field. Indonesia and the United Kingdom follow India with high numbers of publications and citations. In addition, Finland and the USA stand out with high citation rates with a more limited number of publications, indicating that the qualitative impact of studies in these countries is strong. These findings suggest that there is a concentration in the digital banking literature, especially in Asia and Europe, and that these regions can be considered as priority research centers for international collaboration.

Table 1. Countries with the most publications and citations

Country	Documents	Citations
India	218	1472
United Kingdom	48	897
Indonesia	144	785
Finland	7	447
United States	35	442
Saudi Arabia	20	350
Malaysia	48	311
Germany	13	294
China	28	270

Source: Scopus Database, 2025

The construction of research networks plays a decisive role in the level of academic productivity and the impact of research outputs. Indeed, Uwizeye et al. (2022) found that advanced academic collaborations create a favorable scientific environment that increases the productivity of researchers. In this context, identifying the authors who have contributed the most to the digital banking literature is important both to increase scientific interaction and to strengthen the flow of information in the literature.

Table 2. Top 10 authors with the most publications on digital banking

Author	Documents
Rajesh, A.	14
Gui, A.	12
Bhatnagr,P.	9
Karjaluoto, H.	5
Misra, R.	5
Shaikh, A.A.	5
Bhasin, N.K.	5
Wodo, W.	5
Kurniawan, Y.	5
Musyaffi, A.M.	4

Source: Scopus Database, 2025

According to Table 2, the most published author is Rajesh, A. (n=14), followed by Gui, A. (n=12) and Bhatnagr, P. (n=9). In addition, authors such as Karjaluoto, H., Shaikh, A.A., Bhasin, N.K. and Wodo, W. also stand out with high productivity levels. The contributions of these authors to the literature show who is producing the studies that constitute the knowledge base of the field; therefore, they also provide strategic data for structuring potential collaboration networks. Identifying active researchers not only increases the impact of publications, but also facilitates the sharing and development of knowledge at the interdisciplinary level.

Identifying the authors leading the literature in the field of digital banking is important to focus on studies with high scientific impact and to evaluate potential research collaborations. The most cited authors in this field are shown in Table 3.

Table 3. Most cited authors

Author	Citations
Karjaluoto, H.	361
Shaikh, A.A.	361
Saarijärvi, H.	244
Saraniemi, S.	244
Grima, S.	185
Kaur, B.	169
Kiran, S.	169
Rupeika-A.R.	169
Spigt, R.	131
Swinkels, L.	131

Source: Scopus Database, 2025

According to the citation analysis in the study, the authors with the highest impact on the literature in the field of digital banking have been identified. Karjaluoto, H. and Shaikh, A.A. are the leaders in terms of contribution to the field, with 361 citations per capita. Their high citation levels can be explained not only by their productivity but also by the fact that their published work is widely cited by the scientific community. They are followed by Saarijärvi, H. and Saraniemi, S.; each of them has 244 citations, making their theoretical and methodological contributions to the field significantly visible. The common feature of these four authors is that they focus on themes such as user behavior, service quality, digital financing and customer experience related to digital transformation processes in the banking sector. In addition, researchers such as Grima, S., Kaur, B., Kiran, S. and Rupeika-Apoga, R. rank high with between 169 and 185 citations and contribute to the literature with regional or thematic focused studies. Spigt, R. and Swinkels, L. round out the list with 131 citations and their work contributes to the development of important sub-themes in the field. The network map of the most cited authors in this field is shown in Figure 4.

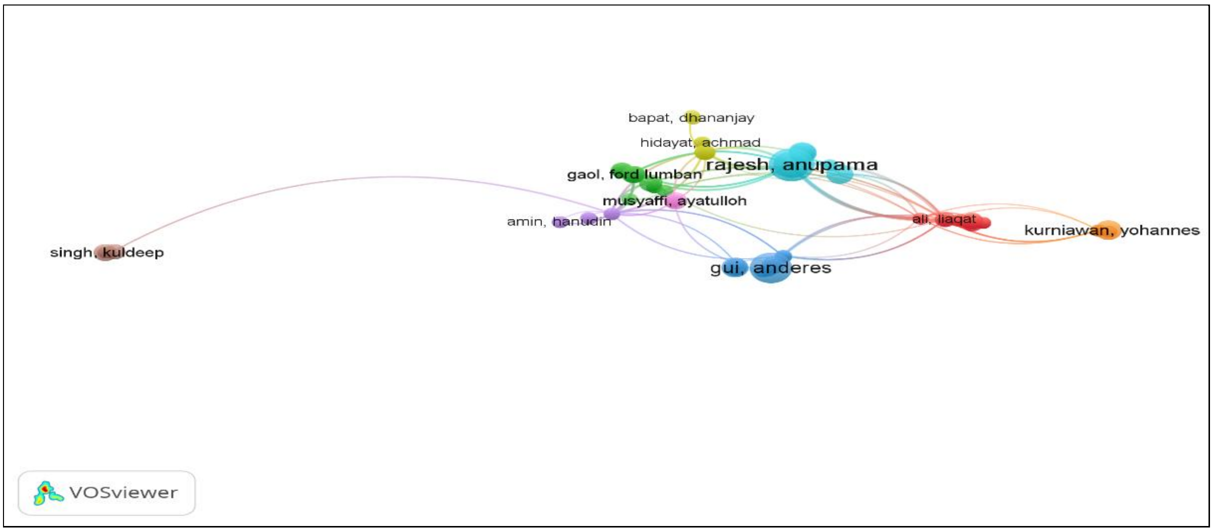

Figure 4. Network map of most cited authors

These findings reveal that not only productivity but also the level of scholarly impact varies significantly across authors in the digital banking literature. Highly cited authors in particular play a central role in shaping the theoretical depth of the field and guiding future research directions.

Organization-based analyses in scientific research are important in determining the level of contribution of institutions to the literature and their position in research networks. In this context, identifying the most influential academic institutions in line with the number of citations also contributes to the evaluation of cooperation opportunities at the institutional level.

Table 4. The most cited institution on digital banking

Organization	Citations
Jyväskylä University School of Business and Economics	300
Oulu Business School at University of Oulu	244
School of Management at University of Vaasa	244
Chair for Banking and Finance, Zeppelin University, Germany	216
College of Business and Economics, Qatar University	216
Zeppelin University, Am Seemoser Horn, Germany	216
Durham University, United Kingdom	176
Federal Reserve Bank of Philadelphia, United States	176
Imperial College London, United Kingdom	176
Sheffield Hallam University, Sheffield, United Kingdom	170

Source: Scopus Database, 2025

In the analysis of 1644 organizations in total, the top 10 institutions with the highest impact among the 838 institutions with more than 1 citation are presented in Table 4. Accordingly, Jyväskylä University School of Business and Economics is the institution with the highest concentration of academic contribution in the field of digital banking, with 300 citations. It is followed by Oulu Business School at University of Oulu and School of Management at University of Vaasa (244 citations each). Zeppelin University (Germany) and Qatar University stand out with 216 citations each, while prestigious institutions such as Durham University, Federal Reserve Bank of Philadelphia, and Imperial College London contribute significantly to the literature with 176 citations.

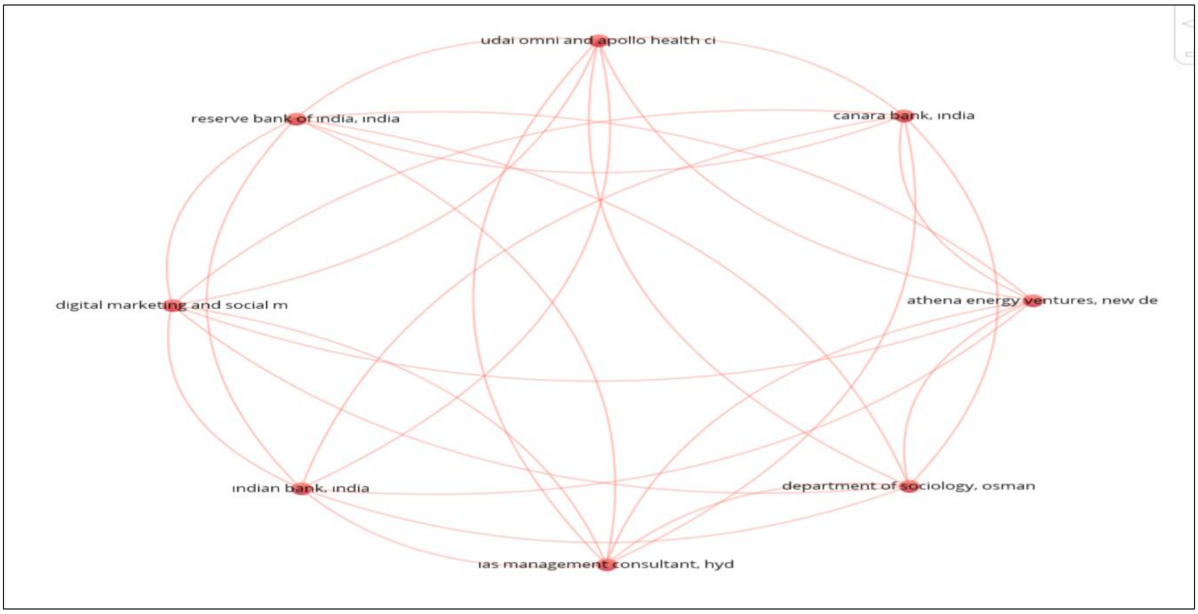

Figure 5. Inter-organizational network structure

The inter-organizational network structure in Figure 5 shows a dense network of connections, especially among India-based institutions. The graph represents institutional interactions based on co-citation and thematic proximity, and also indicates the existence of specific geographical clusters. This suggests that some countries (especially India) are central to the production of research in the digital banking literature, both at the institutional and regional level.

In terms of evaluating publication trends in the scientific literature, source (journal) level analyses are an important tool to understand the academic platforms in which a particular topic is concentrated and its interdisciplinary diffusion. Identifying the prominent journals according to the number of publications contributes to the identification of academic visibility and knowledge production centers in the relevant fields.

Table 5. Journals with the highest number of publications on digital banking

Source	Documents
Lecture Notes in Networks and Systems	23
ACM International Conference Proceeding Series	18
Banks and Bank Systems	12
Journal of Financial Services Marketing	11
International Journal of Bank Marketing	11
Communications in Computer and Information Science	11
Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)	10
Studies in Systems, Decision and Control	7
Advances in Intelligent Systems and Computing	7
Procedia Computer Science	5

Source: Scopus Database, 2025

In the analysis of 385 academic sources, the top 10 journals with the highest number of publications are presented in Table 5. At the top of the list, Lecture Notes in Networks and Systems tops the list with 23 publications, indicating that it is the preferred publishing platform for digital banking studies. This journal is followed by ACM International Conference Proceeding Series (18 publications) and Banks and Bank Systems (12 publications).

Another noteworthy finding is that in addition to banking and finance themed journals, computer science and information systems oriented journals also occupy a large place in the list. In particular, Journal of Financial Services Marketing, International Journal of Bank Marketing and Communications in Computer and Information Science point to the interdisciplinary nature of digital banking studies.

In addition, the inclusion of conference series such as Lecture Notes in Computer Science and Studies in Systems, Decision and Control reveals that publications in the field are presented not only in peer-reviewed journals but also extensively in international conference settings. The network graph of journals publishing on digital banking is presented in Figure 6.

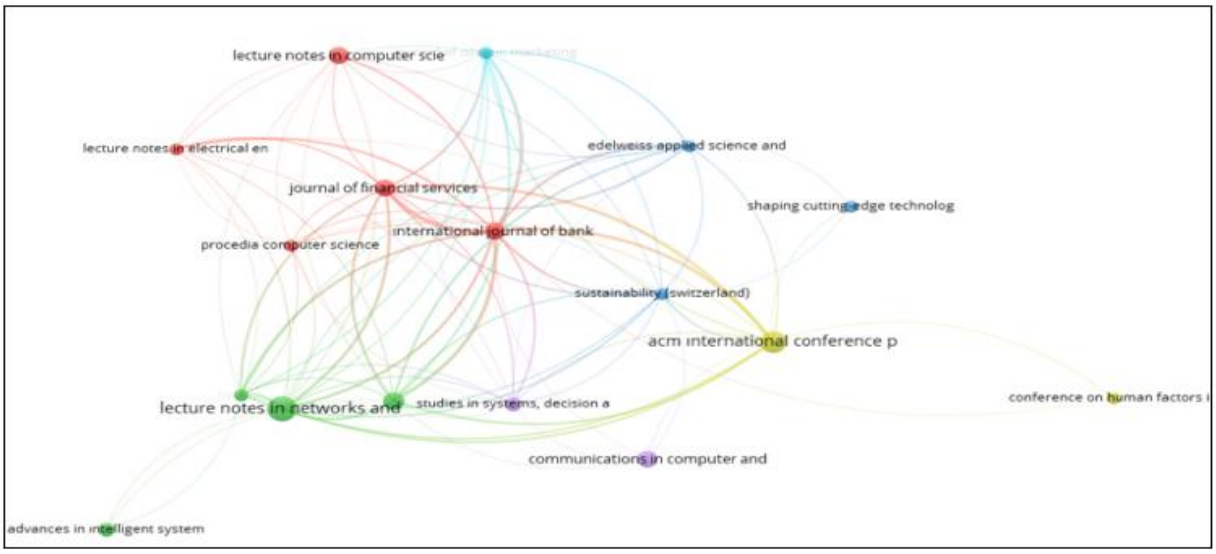

Figure 6. Network graph of journals publishing on digital banking

These findings show that the literature on digital banking is not only limited to finance and banking disciplines, but is also integrated with computer science, artificial intelligence, decision support systems and information technology. This confirms that the subject is multidisciplinary in nature.

In order to assess the academic impact of a research field, not only the number of publications but also the number of citations is a critical criterion. Citation levels reflect the visibility of scientific studies in the field and the degree to which their contribution to knowledge production is recognized. Accordingly, analyzing the most cited journals enables us to identify the academic platforms where the digital banking literature has an impact.

Table 6. Most cited journals on digital banking

Source	Citations
International Journal of Information Management	460
International Journal of Bank Marketing	423
Journal of Financial Services Marketing	402
Finance Research Letters	225
Risks	186
Journal of International Money and Finance	176
Journal of Open Innovation: Technology, Market, and Complexity	140
International Journal of Quality and Service Sciences	135
Financial Innovation	133
Journal of Asian Finance, Economics and Business	129

Source: Scopus Database, 2025

In the analysis of 571 academic sources, the top 10 journals with the highest number of citations are presented in Table 6. The International Journal of Information Management tops the list with 460 citations, indicating that it is a strategic publishing platform at the intersection of digitalization, information management and banking practices.

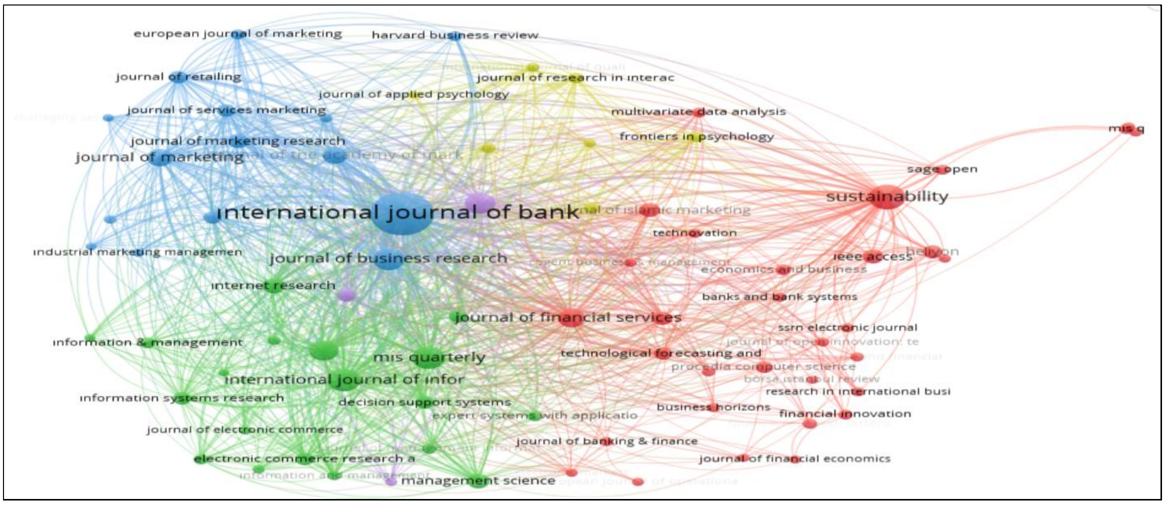

Figure 7. Network graph of the most cited journals

The network graph of the most cited journals is shown in Figure 7. As shown in Figure 7, Journals focusing on banking and financial marketing, such as the International Journal of Bank Marketing (423 citations) and the Journal of Financial Services Marketing (402 citations), provide comprehensive coverage of digital banking dimensions such as customer experience, user acceptance and service strategies. Financial theory-based journals such as Finance Research Letters and Risks make visible the relationship between digital banking issues and risk management and market behavior, while interdisciplinary platforms such as the Journal of Open Innovation show that approaches in the context of technological innovation are integrated into the literature.

These findings suggest that digital banking research is not limited to industry-specific publications, but also finds academic resonance in multidimensional fields such as information systems, quality management, service sciences and financial innovation. These highly cited journals are carriers of key theoretical and applied contributions in the literature.

Table 7. The most cited articles from the studies on digital banking

Cited Reference	Citations
Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes, 50*(2), 179-211.	18
Hair, J. F., Risher, J. J., Sarstedt, M., & Ringle, C. M. (2019). When to use and how to report the results of PLS-SEM. *European Business Review*, *31*(1), 2-24.	16
Ozili, P. K. (2018). Impact of digital finance on financial inclusion and stability. *Borsa Istanbul Review*, *18*(4), 329-340.	15
Kitsios, F., Giatsidis, I., & Kamariotou, M. (2021). Digital transformation and strategy in the banking sector: Evaluating the acceptance rate of e-services. *Journal of Open Innovation: Technology, Market, and Complexity*, *7*(3), 204.	15
Davis, F. D., Bagozzi, R. P., & Warshaw, P. R. (1989). User acceptance of computer technology: A comparison of two theoretical models. *Management Science*, *35*(8), 982-1003.	14
Baptista, G., & Oliveira, T. (2015). Understanding mobile banking: The unified theory of acceptance and use of technology combined with cultural moderators. *Computers in Human Behavior*, *50*, 418-430.	14
Venkatesh, V., & Davis, F. D. (2000). A theoretical extension of the technology acceptance model: Four longitudinal field studies. *Management Science*, *46*(2), 186-204.	13
Fornell, C., & Larcker, D. F. (1981). Evaluating structural equation models with unobservable variables and measurement error. *Journal of Marketing Research*, *18*(1), 39-50.	13
Pikkarainen, T., Pikkarainen, K., Karjaluoto, H., & Pahnila, S. (2004). Consumer acceptance of online banking: An extension of the technology acceptance model. *Internet Research*, *14*(3), 224-235.	13
Alalwan, A. A., Dwivedi, Y. K., & Rana, N. P. (2017). Factors influencing adoption of mobile banking by Jordanian bank customers: Extending UTAUT2 with trust. *International Journal of Information Management*, *37*(3), 99-110.	12

Source: Scopus Database, 2025

Identifying frequently cited works in the literature is crucial for understanding the theoretical framework and methodological orientations of a research field. The analysis of cited references reveals the key works that constitute the knowledge base of the field, guiding researchers in identifying conceptual orientations and influential contributions. The most frequently cited articles on digital banking are listed in Table 7.

In the study, which includes a total of 35,660 citations, the 10 most influential reference articles that have been cited at least 10 times have been identified. Ajzen (1991)'s *Theory of Planned Behavior*, which tops the list, provides a theoretical basis that is frequently used to explain individuals' behavioral intentions in the context of digital banking with 18 citations. The article developed by Hair et al. (2019), which addresses the reporting standards for the PLS-SEM method, is a methodological reference especially in empirical research using structural equation modeling with 16 citations. Ozili (2018) study on the impact of digital finance on financial inclusion and Kitsios et al.'s (2021) assessment on digital transformation strategies are among the notable contributions with 15 citations each, focusing on applied and topical issues. Moreover, studies based on the *Technology Acceptance Model* (TAM) developed by Davis et al.(1989) and Venkatesh and Davis (2000) reveal the strong influence of user acceptance theories in the digital banking context. The prominence of studies on mobile banking, such as Baptista and Oliveira (2015) and Alalwan et al. (2017), reflects how the impact of digital services on user behavior has been addressed in interdisciplinary research.

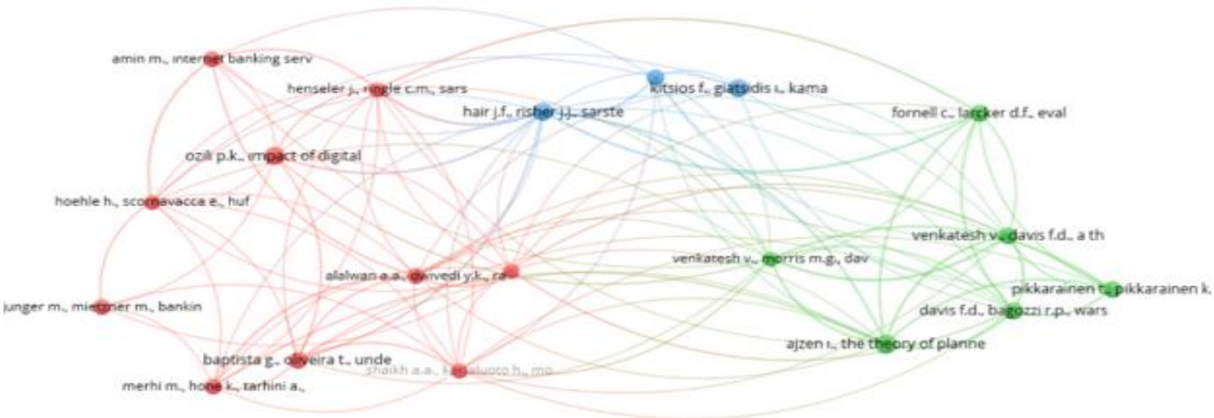

Figure 8. Network map of the most cited articles

Overall, the most cited papers show that theoretical foundations (TAM, TPB, UTAUT2), structural modeling methods (PLS-SEM), policy-oriented issues such as financial inclusion, and user behavior analysis are central to the digital banking literature. This suggests that research in the field focuses on issues of both theoretical soundness and practical value. The network map of the most cited articles is presented in Figure 8.

Table 8. Keyword analysis

Keyword	Occurrences
Digital Banking	330
Fintech	86
Mobile Banking	53
Banking	49
Customer Satisfaction	28
Digitalization	36
Trust	33
Digital Transformation	38
Machine Learning	24
Financial Inclusion	37

Source: Scopus Database, 2025

Keyword analysis is an important method for identifying prominent themes in the literature and understanding the conceptual framework within which research topics are concentrated. Commonly used keywords indicate research trends and key focal points in the field.

According to the analysis results in Table 8, the most frequently used keyword in the field of digital banking was "Digital Banking" (n=330) by far. The high repetition rate of this concept reveals that it constitutes the main axis of the digitalizing financial services literature. This is followed by "Fintech" (n=86), "Mobile Banking" (n=53) and "Banking" in general (n=49). The use of these terms together points to the integration of digital technologies into banking applications and the rise of mobile solutions. User-centered issues also play an important role in the digital transformation process. In particular, terms such as "Customer Satisfaction" (n=28), "Trust" (n=33) and "Digital Transformation" (n=38) indicate a focus on user experience, trust and strategic change processes of organizations. Moreover, the prominence of concepts such as "Machine Learning" (n=24) and "Financial Inclusion" (n=37) indicates that the applications of AI-based technologies in financial services and social dimensions (e.g. financial access) are discussed together in the literature. The network graph of keywords used in studies related to digital banking can be seen in Figure 9.

These findings reveal that digital banking research is not limited to technological infrastructures, but is also multidisciplinary, including user behavior, trust, service quality and social impact.

Figure 9. Network graph of keywords in studies on digital banking

Figure 10 details the temporal distribution of the bibliographic matching analysis and visualizes the prominent studies in the literature periodically. While the map presents the clustering of publications based on reference similarities on the time axis, it reflects the temporal density with color transitions according to the year of publication (between 2020-2025). The circle size is again directly proportional to the number of citations the relevant study has received. The most prominent study in the map is Karjaluoto et al. (2019), which is widely cited and positioned at the center of the literature thanks to its theoretical contributions on digital banking and customer behavior. This is followed by Jünger (2020) and Kaur (2021a), both of which have made significant contributions on user acceptance and technological adaptation to digital finance applications. Looking at the temporal progression, recent studies such as Chen (2024b), Rahman (2024) and Challoumis (2024) are visualized in yellow and are located at the extremes with limited connections. This shows that these studies have not yet formed strong matches in the literature; however, they offer new thematic insights. In particular, publications such as Chen (2024b) can be considered among the pioneering studies that may become central in the literature in the future. In addition, studies such as Wodo (2020b), Moeckel (2019) and Challoumis (2024), which are in the outer ring, differ from other publications in terms of their reference structure and point to more niche or not yet deepened research areas. These publications cover underrepresented themes such as digital transformation in small-scale enterprises, personal data security, AI-enabled banking applications or digital financial infrastructures in developing countries.

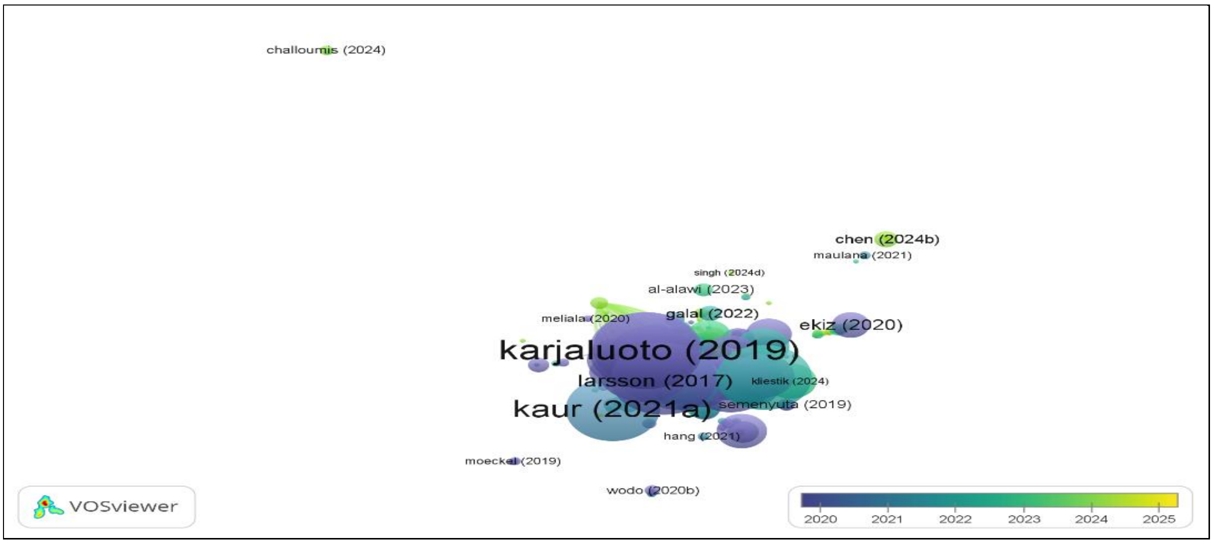

Figure 10. Temporal network graph of keywords in studies on digital banking

5. Conclusion and recommendations

In order to evaluate the academic production on digitalization in the banking sector, this study examined 887 studies in the Scopus database using bibliometric methods and aimed to reveal the structure of the literature. The main objective of the study is to systematically analyze how the digitalization phenomenon is addressed in the field of banking, which themes are prominent, who are the authors, countries and institutions with high academic impact, and in which journals these studies are published.

The bibliographic analysis was carried out through VOSviewer software and the publications were evaluated multidimensionally in terms of author, country, institution, journal, keyword and reference dimensions. As a result of the analysis, it has been determined that the subject of digitalization in banking is a field that has not yet been sufficiently deepened in the literature, and that there has been a significant increase in academic production, especially in the years after 2020. At the country level, India, Indonesia and the United Kingdom make the highest contribution to the literature, while countries such as Finland and the USA also stand out in terms of citation impact. Although Turkey is included in the analysis, it has a limited representation, especially in terms of studies published in journals with high impact factors and international visibility. This shows that digital banking in Turkey has not yet been addressed systematically and qualitatively enough at the academic level.

In the author analysis, Rajesh, Gui and Bhatnagr stand out in terms of productivity, while Karjaluoto and Shaikh stand out in terms of impact with high citation levels. In terms of institutional contribution, Jyväskylä University School of Business and Economics and Oulu Business School stand out, with India-based universities playing central roles in network structures.

The literature analysis revealed that digital banking studies were cited not only in finance-based journals, but also in journals published in the fields of information technology, artificial intelligence and decision sciences. Among the most cited journals were International Journal of Information Management, Journal of Financial Services Marketing and International Journal of Bank Marketing.

The keyword analysis revealed that terms such as "digital banking", "fintech", "financial inclusion" and "digital transformation" are prominent, while sustainability-oriented terms such as "carbon emissions", "energy efficiency" and "ESG" have recently been on the rise. This shows that digitalization is considered not only technologically but also with its environmental and social impacts.

In the temporal bibliographic matching analysis, the presence of publications that do not yet have strong reference matches was noteworthy along with the studies that are central in the literature. These publications point to under-studied and unique research areas and provide important clues for future research.

In conclusion, this study presents a holistic view of academic developments in the field of digital banking, systematically identifying existing gaps, strong actors and future research trends in the field. It is concluded that there is a need for more quality publications in this field, especially in countries such as Turkey, and that there is room for new studies both to increase international visibility and to integrate local contexts into the global digital finance literature.

In line with the findings of this study, several recommendations can be made to support the development of scientific research in the field of digital banking. First, it is essential to increase the number of qualified publications. Academic production in Turkey has been found to be insufficient both in terms of quantity and impact, which makes it necessary to encourage domestic researchers to publish in internationally indexed, high-impact journals and to support research projects and graduate theses on digital banking within universities. At the same time, strengthening interdisciplinary approaches will significantly enhance the scope of the field. As revealed in the keyword analysis, digital banking is closely linked not only to finance but also to information technologies, artificial intelligence, data security, and sustainability; thus, the establishment of multidisciplinary research teams will enable the issue to be addressed more comprehensively. Another important step is the creation of Turkey-focused datasets. Countries such as China, India, and the UK owe their academic visibility in this field to the availability of strong data sources, and producing datasets specific to Turkey's digital banking practices will both open the door to more empirical studies and allow for original contributions.

In addition, fostering collaborations between academic researchers and sectoral actors such as digital financial service providers, fintech companies, regulators, and universities will facilitate the development of practice-oriented academic work. Providing easier access to field data and supporting the translation of academic research into sectoral benefits will further strengthen the link between theory and practice. Furthermore, the findings of bibliographic matching analysis show that some alternative subject areas—such as digitalization in SMEs, digital risk management, and data-driven decision systems—remain relatively underexplored, making them promising topics with novelty value for future research. Finally, future studies can achieve more comprehensive results by expanding the scope of analysis beyond the Scopus database and including other academic indexes such as Web of Science, Dimensions, and Google Scholar. The use of advanced bibliometric techniques, including co-word analysis, descriptive network statistics, and theme development methods, will also add further analytical depth and enrich the academic landscape of digital banking research.

Declaration of competing interest

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

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The views expressed in this study are those of the author.

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