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FINANCIAL DEVELOPMENT, TECHNOLOGICAL INNOVATION, AND ENVIRONMENTAL DEGRADATION: EVIDENCE FROM LOWER-MIDDLE-INCOME COUNTRIES IN ASIA

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ABSTRACT

This study analyzes the causal relationship between financial development and technological innovation, considering their impact on environmental degradation. The data sample covers nineteen lower-middle-income countries in Asia over the period 2000-2021. By using the panel vector autoregression (PVAR), the authors demonstrate the close relationship between financial development and technological innovation. Specifically, technological innovation fosters financial development in both the short and long term, while the latter plays a vital role in driving the former over the long term. Furthermore, financial development is reported to worsen environmental degradation in these countries in both the short and long run. These findings imply that while financial development provides essential financial resources for technological innovation, it may also contribute to environmental degradation by stimulating business activities, investment, and energy consumption. Meanwhile, technological innovation promotes financial development but has not significantly improved the ability to mitigate environmental degradation in these countries. These findings align with the characteristics of lower-middle-income countries, where financial resources for business expansion and technological innovation are prioritized, but measures to stop environmental degradation remain limited. In light of the findings, the study provides recommendations for governments and policymakers in these economies, emphasizing the need to promote financial development coupled with minimizing environmental degradation, particularly by further innovating technology to achieve substantial environmental benefits.

Keywords: *Ecological footprint, environmental degradation, financial development, lower-middle-income, technology innovation*

1. INTRODUCTION

Environmental degradation can stem from economic activities, especially when countries prioritize rapid growth without adequately considering environmental quality (Jinqiao et al., 2022). Environmental degradation has become one of the major global challenges, which is particularly evident in countries pursuing sustainable development (Zameer et al., 2020). In fact, the pursuit of sustainable development requires countries to promote economic growth while ensuring environmental protection (Koondhar et al., 2021; Zhou et al., 2021), meaning that economic growth should be encouraged without intensifying environmental degradation (Godil et al., 2021).

Endogenous growth theory emphasizes the role of national internal factors, particularly capital and technology, in fostering economic development (Romer, 1990). Furthermore, the Environmental Kuznets Curve (EKC) theory clarifies the relationship between income and environmental quality. The combination of these theories confirms that environmental degradation can be significantly influenced by a country's internal factors, with financial development and technological innovation playing a key role (Ling et al., 2022).

The earliest empirical studies on this issue primarily focused on clarifying the role of financial development in economic growth, particularly by promoting investment and production financing. However, achieving high economic growth without considering environmental quality may lead to serious environmental consequences, thereby impeding sustainable development (Ling et al., 2022).

Technological innovation is considered the optimal solution for enabling countries to access environmentally friendly energy sources rather than relying on traditional ones such as oil and natural gas, thereby contributing to reducing environmental degradation (Godil et al., 2021). Empirical studies have highlighted the role of technological innovation in mitigating environmental degradation, as reported by Rafique et al. (2020) and Godil et al. (2021). Although most empirical studies agree that technological innovation can reduce environmental degradation, there remain different perspectives on how to measure technological innovation (Asongu et al., 2018; Dam et al., 2024; Mensah et al., 2018; Ozcan & Apergis, 2018; Elhassan, 2025).

More than that, there may exist a close relationship between financial development and technological innovation (Wang et al., 2024). Specifically, financial development provides essential financial resources to boost technological innovation, enabling companies to utilize energy more effectively, increase productivity without harming the environment, and even lessen environmental degradation (Shoaib et al., 2020). Conversely, technological innovation can support financial development, particularly by integrating advanced technologies to enhance the quality of financial services. This, in turn, helps financial development function well in promoting the use of eco-friendly energy sources among companies, thereby contributing to the reduction of environmental degradation (Jinqiao et al., 2022). Nevertheless, most empirical studies have primarily examined the individual effects of financial development and technological innovation on environmental degradation, without clarifying the causal relationship between the two factors in this impact. This limitation poses challenges in fully understanding their impact on environmental degradation, particularly in demonstrating the multidimensional and complete nature of these factors in efforts to mitigate environmental degradation.

To address the research gaps above, this study focuses on a comprehensive examination of the impact of financial development and technological innovation on environmental degradation in 19 lower-middle-income countries in Asia from 2000 to 2021. Notably, the study also investigates the causal relationship between financial development and technological innovation within the context of their effects on environmental degradation, thereby clarifying the multidimensional essence of the connections among these factors in the model.

The remainder of this paper is structured as follows. Section 2 presents a literature review and the development of hypotheses. Section 3 outlines the methodology and data sample. Section 4 provides an in-depth discussion of the empirical results. The final section offers concluding remarks.

2. LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

This section is outlined into three distinct subsections to provide a comprehensive overview of the literature relevant to this study. First, the authors examine the existing literature on the relationship between financial development and environmental degradation. Next, the authors present a review of the link between technological innovation and environmental degradation.

Finally, the authors delve into the literature on the relationship between financial development and technological innovation. Within each subsection, the authors offer a thorough synthesis of the existing literature and identify gaps that need further exploration.

2. 1. FINANCIAL DEVELOPMENT AND ENVIRONMENTAL DEGRADATION

Financial development can be understood as the improvement of the financial system, with an emphasis on financial institutions and financial markets, and defined by three key criteria: depth, efficiency, and accessibility (Bui & Doan, 2024). In specific, financial markets facilitate the direct flow of capital from suppliers to those in need, while financial institutions act as intermediaries between capital demand and supply. Theoretically, the endogenous growth theory provides insights into the effect of financial development on environmental degradation (Aghion & Howitt, 1992). Accordingly, it emphasizes internal economic factors, especially capital and technology (Romer, 1990). Admittedly, it highlights the role of internal drivers in economic growth (Jinqiao et al., 2022). Besides, the EKC theory offers another explanation for the relationship between financial development and environmental degradation. Specifically, at the early stages of economic growth, a rise in income levels may lead to environmental quality deterioration, resulting in worse environmental degradation. However, when an economy reaches a certain income threshold, environmental quality will be improved, primarily due to technological innovation (Jinqiao et al., 2022). Obviously, the endogenous growth and EKC theories are often used in combination to explain how financial development influences environmental degradation (Ling et al., 2022). Moreover, the scale effect theory provides another perspective on this relationship (Grossman & Helpman, 1991). Particularly, financial development expands production scale, thereby intensifying environmental degradation (Koçak & Şarkgüneşi, 2018).

Environmental degradation is an increasingly prevalent global phenomenon, boosting countries to implement suitable policies aimed at achieving sustainable development (Zameer et al., 2020), which needs to foster economic growth together with improving environmental quality (Godil et al., 2021). In fact, financial development can promote economic growth by funding investment and production (Rutendo Magwedere & Marozva, 2025). This serves as a crucial driver of economic expansion but may also increase environmental degradation, thereby reducing environmental quality (Shahbaz et al., 2013). Most empirical studies have focused on examining the impact of financial development on economic growth, with little attention given to its effects on environmental degradation. Specifically, a large number of empirical research on this topic primarily investigated the effect of financial development on economic growth. Accordingly, financial development has been found to boost economic expansion by improving capital allocation efficiency (Cherif & Dreger, 2016) and increasing investment (Botev et al., 2019). Recently, more empirical studies have begun to analyze the relationship between financial development and environmental degradation, but their findings remain contradictory. Some of them confirm that financial development can lead to more severe environmental degradation (Saidi & Mbarek, 2017). According to the EKC theory, this relationship is consistent with the early stages of economic growth, where rising income is associated with environmental degradation (Ling et al., 2022). Similarly, this impact aligns with the scale effect theory, which posits that financial development expands the production scale, thereby worsening environmental degradation (Koçak & Şarkgüneşi, 2018). The reality shows that financial development may lead to excessive investment, resulting in the rise of industrial zones, thereby boosting energy consumption, declining environmental quality (Xu et al., 2018), and even destroying the green economy (Pan et al., 2021). At the individual financial level, improved financial accessibility can enhance consumer purchasing power, which may have negative environmental consequences, particularly with increased resource consumption (Ullah et al., 2023).

Financial development has been empirically confirmed to amplify environmental degradation, particularly in emerging and developing countries (Tang & Tan, 2015). Indeed, financial development enables these countries to promote business and industrial activities to drive economic growth, but weak environmental regulations have led to more severe environmental degradation. In many developing nations, economic growth is often more valued than environmental conservation (Jinqiao et al., 2022). Also, these countries are in the early stages of development and frequently encounter difficulties in accessing advanced and eco-friendly technologies (Razzaq et al., 2021). As evidence, Kihombo et al. (2021) asserted that financial development deteriorates environmental quality in West Asian and Middle Eastern countries. More recently, Wijethunga et al. (2023) revealed a negative impact of financial development on environmental quality in Sri Lanka.

Regarding the measurement, most researchers commonly identify environmental degradation through CO_2 emissions (Jinqiao et al., 2022). However, some studies have utilized the ecological footprint as an alternative measure of environmental quality. For instance, Danish et al. (2019) concluded that financial development expands the ecological footprint across 59 Belt and Road Initiative (BRI) countries. Likewise, Saud et al. (2020) revealed that financial development contributes to a higher ecological footprint in BRI countries. Also, Koondhar et al. (2021) affirmed that financial development leads to an increase in Japan's ecological footprint.

Meanwhile, several studies have demonstrated that financial development can mitigate environmental degradation (Adams et al., 2018), especially when financial resources are effectively allocated to promote the use of advanced and environmentally friendly energy sources and technologies (Zameer et al., 2019). In fact, the financial system can contribute to environmental conservation by providing credit for green projects (Moraliyska, 2023). By simplifying lending procedures, it can facilitate investment in renewable energy projects (Saadaoui & Chtourou, 2023; Socotar & Gabor, 2024). Empirical evidence proves that financial development can reduce environmental degradation, which is commonly observed in developed countries (Khrisat & Alqadi, 2023). In these countries, great awareness of the consequences of environmental pollution, coupled with strict environmental regulations, has stimulated companies to adopt eco-friendly energy sources, thereby fostering economic growth in conjunction with environmental quality improvements (Jinqiao et al., 2022). This view is in agreement with Sadorsky (2011) and Chang (2015), who reported that financial development impedes green growth in low- and middle-income countries, whereas its positive impact on green growth is more evident in advanced ones. Similarly, Ganda (2020) identified a negative link between financial development and CO_2 emissions in the Organization for Economic Cooperation and Development (OECD) countries. Fakher et al. (2021) analyzed data from the Organization of the Petroleum Exporting Countries (OPEC) nations and reported that financial development serves as a foundation for enhancing the sustainability of environmental quality in these countries. Prempeh (2023) affirmed that financial development can reduce environmental degradation in 10 countries within the Economic Community of West African States (ECOWAS). Using ecological footprint as a measure of environmental degradation, Uddin et al. (2017), Ahmed et al. (2019), and Baloch et al. (2021) found that financial development contributes to the decrease in ecological footprint in 27 countries, Malaysia, and OECD countries, respectively.

It is evident that contradictory views exist regarding the impact of financial development on environmental degradation. One of the primary reasons for these contrasting perspectives is the dependence on the efficiency in utilizing financial resources and the specific characteristics of individual countries (Shoaib et al., 2020). In lower-middle-income countries, financial development is often prioritized as a key driver of economic growth, while its potential contribution to environmental degradation is overlooked (Jinqiao et al., 2022). This impact is mentioned by the endogenous growth (Aghion & Howitt, 1992), EKC (Ling et al., 2022), and scale effect theories (Koçak & Şarkgüneşi, 2018). Empirical studies have also supported this relationship in the context of developing countries (Tang & Tan, 2015). On this foundation, the first research hypothesis is proposed as follows:

Hypothesis H_1: *Financial development contributes to increased environmental degradation in lower-middle-income countries in Asia.*

2. 2. TECHNOLOGICAL INNOVATION AND ENVIRONMENTAL DEGRADATION

The endogenous growth theory can be combined with the EKC theory to explain the influence of technological innovation on environmental degradation (Jinqiao et al., 2022). The former emphasizes that capital and production factors are not the only drivers of growth, but technological innovation should be considered in this impact (Shoaib et al., 2020). Meanwhile, the latter highlights that promoting economic growth can lead to increased environmental degradation. However, when an economy achieves a certain income level, environmental quality begins to recover, mainly due to advancements in technology (Jinqiao et al., 2022). Therefore, both theories support a close relationship between technological innovation and environmental degradation. In addition, the technological effect theory underscores that the adoption of advanced technology benefits the environment (Koçak & Şarkgüneşi, 2018). These theories provide critical foundations for the importance of technological innovation in minimizing environmental degradation (Jinqiao et al., 2022).

Technological innovation is considered the optimal solution for encouraging the industrial sector's approach to environmentally friendly energy sources, rather than using conventional sources such as oil and natural gas. This enhances production efficiency and reduces CO_2 emissions, thereby mitigating environmental degradation (Godil et al., 2021). In fact, the role of technological innovation in reducing environmental degradation has been confirmed by several empirical studies. For instance, Rafique et al. (2020) and Godil et al. (2021) confirmed that technological innovation contributes to lowering CO_2 emissions and improving environmental quality. Kumail et al. (2020) revealed that technological innovation improves environmental quality in Pakistan and EU countries by limiting the use of fossil fuels. Moreover, Li et al. (2021) and Nathaniel et al. (2021) demonstrated that technological innovation enables the development of environmental technologies that mitigate the negative impact of waste on the environment. Luo et al. (2021)this study investigated the influence of green investment, technology innovations, and economic growth on CO2 emissions in selected Asian countries for the period 2001 to 2019. The Cross-Section dependency (CSD confirmed that technological innovation significantly reduces CO_2 emissions and fosters sustainability across Asian countries. Jianguo et al. (2022) argued that while financial development increases CO_2 emissions, technological innovation can limit them in 37 OECD countries. Admittedly, the role of technological innovation in reducing environmental degradation is particularly evident in developing and emerging economies (Shoaib et al., 2020). This is because these countries often face higher levels of environmental pollution than developed nations, so technological innovation is regarded as an effective solution to address this issue. Indeed, Bekun et al. (2021) noted that emerging economies usually have higher CO_2 emissions than developed countries, making technological innovation crucial in controlling environmental degradation there. Baloch et al. (2021) also reported the importance of technological innovation in emerging countries, even in deactivating the adverse environmental effects of financial development. However, although most empirical studies have affirmed the positive impact of technological innovation on environmental quality, some studies present different viewpoints. For example, Koondhar et al.

(2021) and Usman and Hammar (2021) asserted that the use of modern technologies may lead to increased CO_2 emissions due to the overuse of fossil fuels. This suggests that while modern technologies can boost production, neglecting environmental protection can have detrimental effects on the environment.

Although most empirical studies acknowledge that technological innovation can reduce environmental degradation, there remain contradictory perspectives on how to measure the former. Indeed, some studies measure technological innovation through R&D activities. For instance, Mensah et al. (2018) analyzed a dataset from 28 OECD countries and affirmed that while economic growth increases CO_2 emissions, strengthening R&D can significantly reduce them. Furthermore, some studies have focused on examining the influence of ICT on the environment. Asongu et al. (2018) concluded that the adoption of advanced ICT can reduce CO_2 emissions and enhance environmental quality in Sub-Saharan African countries. Similarly, Ozcan and Apergis (2018) demonstrated that ICT can considerably minimize environmental degradation in emerging economies. Most prior studies have also commonly measured technological innovation using the number of patent applications. For example, Ercan et al. (2024)the role of technological innovations and income inequality on pollution is a relatively recent discussion in the studies testing the EKC hypothesis. The aim of this paper is to investigate the impact of technological innovations, income inequality, exports, urbanization, and growth on CO 2 emissions in EU-27. In addition, while investigating this relationship, exports and urbanization are also considered and panel vector autoregression (PVAR reported that technological innovation reduces CO_2 emissions in EU-27 countries, where technological innovation is measured by the number of patent applications.

Regarding the measurement of environmental degradation, a substantial body of empirical studies has measured it through CO_2 emissions, including those by Bekun et al. (2021), Koondhar et al. (2021), Luo et al. (2021)this study investigated the influence of green investment, technology innovations, and economic growth on CO2 emissions in selected Asian countries for the period 2001 to 2019. The Cross-Section dependency (CSD, Usman and Hammar (2021), Jianguo et al. (2022), and Ercan et al. (2024)the role of technological innovations and income inequality on pollution is a relatively recent discussion in the studies testing the EKC hypothesis. The aim of this paper is to investigate the impact of technological innovations, income inequality, exports, urbanization, and growth on CO 2 emissions in EU-27. In addition, while investigating this relationship, exports and urbanization are also considered and panel vector autoregression (PVAR. Meanwhile, other studies have utilized the ecological footprint as a measure of environmental degradation which is expected to provide a more comprehensive assessment of environmental quality. Ahmed et al. (2020) concluded that technological innovation is a prerequisite for diminishing the ecological footprint in developing economies. Ke et al. (2020) argued that technological innovation improves environmental quality by reducing the ecological footprint in China. Similarly, Mahmood et al. (2020) found a stable and long-term relationship between technological innovation and the ecological footprint. Fakher et al. (2023) measured environmental degradation across 25 economies using the ecological footprint and confirmed that while financial development accelerates environmental degradation, technological innovation can enhance environmental quality. Recently, Dam et al. (2024) asserted that technological innovation minimizes the ecological footprint in E-7 countries including Brazil, China, India, Indonesia, Mexico, Russia, and Türkiye. Nonetheless, some studies, such as those of Sabir and Gorus (2019) conducted in South Asian countries, and Destek and Manga (2021) implemented in emerging countries, have revealed that the insignificant effect of technological innovation on the ecological footprint.

The impact of technological innovation on environmental degradation has been demonstrated in a big number of empirical researches. However, there remain conflicting views regarding the extent of this effect, particularly due to the lack of consensus on how to assess technological innovation and environmental degradation. This presents intriguing research gaps that need further investigation. In this study, the authors analyze a dataset of the lower-middle-income countries. Therefore, technological innovation is expected to be the best solution for diminishing environmental degradation in these countries Shoaib et al. (2020). This impact aligns with the endogenous growth and the EKC theories (Shoaib et al., 2020), as well as with the technological effect theory (Koçak & Şarkgüneşi, 2018). Based on this foundation, the second hypothesis is proposed as follows:

Hypothesis H_2: *Technological innovation plays a role in mitigating environmental degradation in lower-middle-income countries in Asia.*

2. 3. FINANCIAL DEVELOPMENT AND TECHNOLOGICAL INNOVATION

Financial development provides essential resources for companies in the process of technological innovation, which aligns with the endogenous growth theory (Rafique et al., 2020). Accordingly, financial development and technological innovation serve as important endogenous factors, especially in supporting each other to promote sustainable development. In fact, companies facing difficulties in accessing financial resources often struggle to invest in R&D and technological innovation (Brown et al., 2012). The nexus between financial development and technological innovation has been revealed in several empirical studies. Some studies identify that this relationship can considerably influence environmental degradation. Specifically, financial development supplies critical financial resources to boost technological innovation. This, in turn, enables companies to utilize energy more efficiently, enhancing productivity without harming the environment, and even alleviating environmental degradation in some cases (Shoaib et al., 2020). Consequently, technological innovation is expected to serve as an optimal solution for neutralizing the negative environmental influence of financial development (Baloch et al., 2021). In empirical research, Romer (1990) stated that financial development promotes investment in R&D, thereby contributing to improvements in environmental quality. Tamazian and Rao (2010) asserted that financial development enhances energy efficiency by allowing firms to adopt new technologies. Yuxiang and Chen (2011) identified financial development as a critical foundation for technology diffusion and CO_2 emission reduction. Meanwhile, Adebayo et al. (2021) affirmed that the number of patent applications can reduce the negative environmental effects of financial development.

On the other hand, technological innovation can support financial development, particularly by integrating advanced technologies to enhance the quality of financial services. This, in turn, enables financial development to effectively enhance production activities that utilize environmentally friendly energy sources, thereby contributing to reducing environmental degradation (Jinqiao et al., 2022). In recent years, the role of technological innovation in improving financial service quality and enhancing environmental quality has received considerable attention from researchers (Godil et al., 2021). Indeed, technological innovation not only facilitates the advancement of financial services but also helps companies access eco-friendly energy sources, thereby fostering productivity and simultaneously reducing CO_2 emissions (Jinqiao et al., 2022; Mensah et al., 2018). More importantly, technological innovation is regarded as an effective solution for enhancing the efficiency of financial resource utilization and quickening environmental quality improvements (Jinqiao et al., 2022). Accordingly, several empirical studies have identified technological innovation, particularly measured by the quantity of patent applications, as a key factor in diminishing the negative environmental impacts of financial development (Adebayo et al., 2021; Baloch et al., 2021). Some researchers even argue that technological innovation is a prominent solution for neutralizing the negative impact of financial development on the environment (Baloch et al., 2021)financial development is leading toward a higher rate of economic expansion and promoting energy innovation around the globe. Nevertheless, environmental impact of financial development has preoccupied government officials to circumvent adverse impact on environmental quality. Thus, this paper examines the nexus between financial development, economic growth, energy innovation, and environmental pollution for the period of 1990–2017 for the panel of Organization for Economic Cooperation and Development (OECD. Therefore, the role of technological innovation in optimizing the use of financial resources to enhance environmental quality has attracted significant global attention, particularly among developing economies (Solarin et al., 2021).

By reviewing the current literature, it is evident that financial development provides crucial financial resources to promote technological innovation. Also, technological innovation can create favorable conditions for countries to enhance their level of financial development. Therefore, financial development and technological innovation may exhibit a causal relationship, with the primary trend being positive. Furthermore, this link can exert a significant effect on environmental degradation. Based on this foundation, the authors propose the research hypothesis as follows:

Hypothesis H_3: *Financial development has a positive relationship with technological innovation in low-middle-income countries in Asia.*

3. RESEARCH DESIGN

3. 1. RESEARCH MODEL

The existing literature has demonstrated that environmental degradation is significantly influenced by financial development and technological innovation (Jianguo et al., 2022; Jinqiao et al., 2022; Ullah et al., 2023). Furthermore, there may exist a close connection between financial development and technological innovation, which can change the influence of each factor on environmental degradation. This has been suggested in previous studies by Mensah et al. (2018), Adebayo et al. (2021), and Jinqiao et al. (2022). Following this, the authors model this simultaneous relationship using the panel vector autoregression (PVAR) approach developed by Abrigo and Love (2016). This approach is appropriate as it leverages the benefits of panel data estimation techniques while allowing for an examination of the relationships between variables in the research model (Abrigo & Love, 2016). Moreover, the Granger causality test is employed to investigate the causal relationships among the variables, which was also adopted in prior research by Ercan et al. (2024)the role of technological innovations and income inequality on pollution is a relatively recent discussion in the studies testing the EKC hypothesis. The aim of this paper is to investigate the impact of technological innovations, income inequality, exports, urbanization, and growth on CO 2 emissions in EU-27. In addition, while investigating this relationship, exports and urbanization are also considered and panel vector autoregression (PVAR. The research model equations are constructed using the PVAR approach as follows:

$$ED_{it} = \alpha_0 + \sum_{k=1}^{n} \alpha_{1k} ED_{it-k} + \sum_{k=1}^{n} \alpha_{2k} FD_{it-k} + \sum_{k=1}^{n} \alpha_{3k} TI_{it-k} + \sum_{k=1}^{n} \alpha_{4k} X_{it-k} + \mu_{1i} + \varepsilon_{1it} \quad (1)$$

$$FD_{it} = \beta_0 + \sum_{k=1}^{n} \beta_{1k} ED_{it-k} + \sum_{k=1}^{n} \beta_{2k} FD_{it-k} + \sum_{k=1}^{n} \beta_{3k} TI_{it-k} + \sum_{k=1}^{n} \beta_{4k} X_{it-k} + \mu_{2i} + \varepsilon_{2it} \quad (2)$$

$$TI_{it} = \delta_0 + \sum_{k=1}^{n} \delta_{1k} ED_{it-k} + \sum_{k=1}^{n} \delta_{2k} FD_{it-k} + \sum_{k=1}^{n} \delta_{3k} TI_{it-k} + \sum_{k=1}^{n} \delta_{4k} X_{it-k} + \mu_{3i} + \varepsilon_{3it} \quad (3)$$

In specific, Equation (1) focuses on examining the impact of financial development (FD) and technological innovation (TI) on environmental degradation (ED). Equation (2) is designed to analyze the influence of environmental degradation (ED) and technological innovation (TI) on financial development (FD), while Equation (3) investigates the effect of environmental degradation (ED) and financial development (FD) on technological innovation (TI). Besides, the authors incorporate control variables (X) into the research model. In the model, i represents each country under study, where $i = 1, 2, \ldots, n$; t denotes the study period, where $t = 1, 2, \ldots, T$; k is the selected optimal lag length. $\boldsymbol{\mu}$ captures a country-specific effect, while $\boldsymbol{\varepsilon}$ represents the error terms of the model.

3. 2. SAMPLE AND DATA SOURCES

The dataset includes 19 lower-middle-income countries in Asia, covering the period from 2000 to 2021. The dataset excludes the periods with incomplete data. The classification of lower-middle-income countries follows the World Bank (WB) criteria, specifically including those with a per capita Gross National Income (GNI) ranging from 1,136 USD to 4,465 USD. The list of these countries is presented in Table 1.

Table 1. List of countries

Bangladesh	Jordan	Myanmar	Tajikistan
Bhutan	Kyrgyz Republic	Nepal	Timor-Leste
Cambodia	Lao PDR	Pakistan	Uzbekistan
India	Lebanon	The Philippines	Vietnam
Iran	Mongolia	Sri Lanka	

Source: Authors' proposal

In this study, environmental degradation (ED) is measured using the ecological footprint (global hectares per capita), with data calculated and published by the Global Footprint Network (GFN). In the existing literature, a substantial number of empirical studies have estimated environmental degradation through CO_2 emissions, including those of Bekun et al. (2021), Koondhar et al. (2021), Luo et al. (2021)this study investigated the influence of green investment, technology innovations, and economic growth on CO2 emissions in selected Asian countries for the period 2001 to 2019. The Cross-Section dependency (CSD, Usman and Hammar (2021), Jianguo et al. (2022), and Ercan et al. (2024)the role of technological innovations and income inequality on pollution is a relatively recent discussion in the studies testing the EKC hypothesis. The aim of this paper is to investigate the impact of technological innovations, income inequality, exports, urbanization, and growth on CO 2 emissions in EU-27. In addition, while investigating this relationship, exports and urbanization are also considered and panel vector autoregression (PVAR. However, this measurement has limitations when focusing solely on air pollution. In contrast, the ecological footprint provides a more comprehensive and holistic assessment of environmental degradation by encompassing air, land, and water resources (Baigorri et al., 2025). Therefore, the authors adopt the ecological footprint as the measure of environmental degradation in this study. This approach has also been employed in previous studies, including those by Ahmed et al. (2020), Ke et al. (2020), Mahmood et al. (2020), Saud et al. (2020), Ahmed et al. (2021), Baloch et al. (2021), Fakher et al. (2023), Ullah et al. (2023), Shi et al. (2024) and Dam et al. (2024).

Financial development (FD) is measured by the financial development index, which is calculated and published by the International Monetary Fund (IMF). This index reflects the level of financial sector development, highlighting the advancement of financial markets and financial institutions. This measure has also been used in previous studies, including those by Jianguo et al. (2022) and Ullah et al. (2023).

Technological innovation (TI) is identified as the logarithm of the total number of patent applications (residents and non-residents). This measurement allows for the observation of actual innovation outcomes in each country, following the findings of Jianguo et al. (2022), Jinqiao et al. (2022), Fakher et al. (2023), Ullah et al. (2023), Dam et al. (2024), and Ercan et al. (2024) the role of technological innovations and income inequality on pollution is a relatively recent discussion in the studies testing the EKC hypothesis. The aim of this paper is to investigate the impact of technological innovations, income inequality, exports, urbanization, and growth on CO 2 emissions in EU-27. In addition, while investigating this relationship, exports and urbanization are also considered and panel vector autoregression (PVAR.

The control variables (X) include GDP growth (GG), economic globalization (EG), and population growth (PG). Specifically, GDP growth (GG) is determined by the annual growth rate of GDP per capita, as done in prior studies by Jianguo et al. (2022), Jinqiao et al. (2022), Fakher et al. (2023), and Dam et al. (2024). Economic globalization (EG) is estimated by the economic globalization index, which reflects the level of connection among countries, particularly through the movement of financial resources, and trade in goods and services (Ullah et al., 2023). Population growth (PG) is measured as the annual growth rate of the total population (Jinqiao et al., 2022).

A description of the variables is described in Table 2.

Table 2. Variable definitions

Variables		Descriptions	Data source
Environmental degradation	ED	The ecological footprint (global hectares per capita)	GFN
Financial development	FD	The financial development index	IMF
Technological innovation	TI	The logarithm of the total number of patent applications (residents and non-residents)	WB
GDP growth	GG	GDP per capita growth (annual %)	WB
Economic globalization	EG	The economic globalization index	KOF Swiss Economic Institute
Population growth	PG	Population growth (annual %)	WB

Source: Authors' proposal

4. EMPIRICAL ANALYSIS

4. 1. BASIC STATISTICS

The dataset is obtained from 19 lower-middle-income countries in Asia for the period 2000 -2021. The descriptive statistics of this dataset are presented in Table 3 as follows:

Table 3. Descriptive statistics

Variable	ED	FD	TI	GG	EG	PG
Mean	1.657	0.232	4.333	3.791	48.174	1.550
Std. Dev.	1.493	0.125	3.383	4.373	14.134	1.187
Min.	0.080	0.029	0	-19.750	0	-2.880
Max.	7.770	0.580	11.028	29.980	77.580	11.790
Obs.	418	418	418	418	418	418

Source: Authors' calculation

Table 3 demonstrates that ED has an average value of 1.657, with the lowest one (0.08) observed in Iran in 2014 and the highest one (7.77) recorded in Mongolia in 2020. FD has a mean value of 0.232, with a minimum value (0.029) found in Cambodia in 2001 and a maximum value (0.58) in Jordan in 2008. Regarding TI, the average value is 4.333, corresponding to 2,900.21 patent applications. Its highest value (11.028, equivalent to 61,573 patent applications) was observed in India in 2021. Conversely, other countries, including Cambodia (2000–2006), Timor-Leste (2002–2004), Nepal (2003), and Lao PDR (2002), experienced low levels of technological innovation.

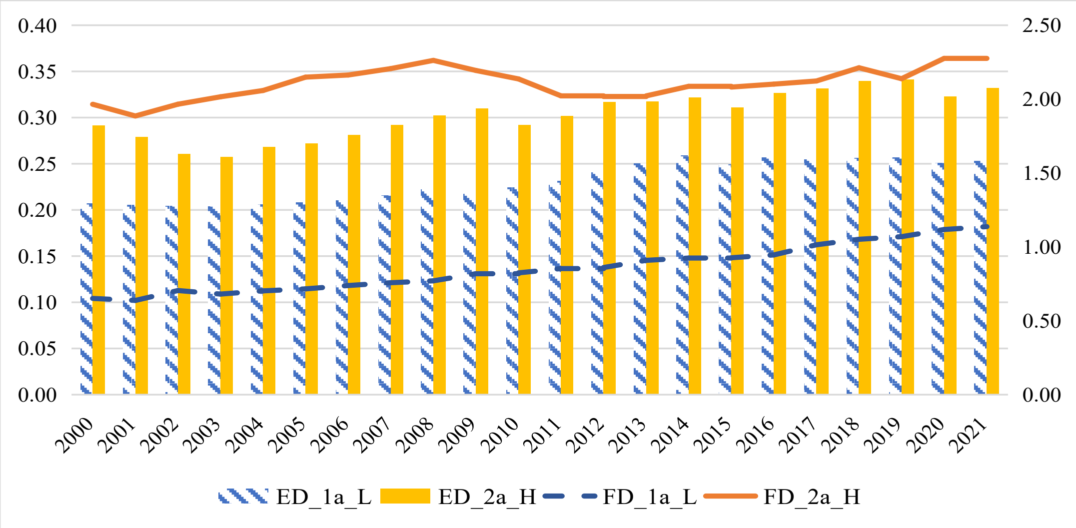
Table 4. Descriptive statistics by country group

Year	Group 1a		Group 2a		Group 1b		Group 2b	
	FD_1a_L	ED_1a_L	FD_2a_H	ED_2a_H	TI_1b_L	ED_1b_L	TI_2b_H	ED_2b_H
2000	0.104	1.293	0.314	1.820	0.838	1.953	6.443	1.086
2001	0.102	1.282	0.302	1.744	1.422	1.873	6.564	1.087
2002	0.113	1.278	0.314	1.626	1.394	1.771	6.722	1.078
2003	0.109	1.273	0.323	1.606	1.416	1.744	6.897	1.083
2004	0.112	1.286	0.329	1.675	1.136	1.768	6.971	1.140
2005	0.115	1.299	0.344	1.699	1.186	1.818	7.161	1.123
2006	0.118	1.314	0.346	1.757	1.317	1.880	7.391	1.128
2007	0.121	1.346	0.353	1.824	1.146	1.931	7.512	1.174
2008	0.123	1.386	0.362	1.888	1.220	2.032	7.572	1.170
2009	0.131	1.358	0.351	1.935	1.867	2.070	6.657	1.144
2010	0.132	1.403	0.342	1.825	1.869	2.001	7.538	1.160
2011	0.137	1.447	0.324	1.884	1.713	2.074	7.472	1.187
2012	0.138	1.504	0.323	1.980	1.868	2.229	6.792	1.174
2013	0.145	1.563	0.323	1.984	3.115	2.316	7.502	1.147
2014	0.148	1.616	0.334	2.011	2.787	2.388	6.841	1.153
2015	0.148	1.557	0.333	1.943	3.041	2.266	6.479	1.155
2016	0.151	1.606	0.336	2.040	2.359	2.380	7.549	1.180
2017	0.162	1.591	0.340	2.071	2.538	2.378	7.482	1.197
2018	0.168	1.601	0.354	2.122	1.654	2.412	7.536	1.221
2019	0.171	1.605	0.342	2.133	1.899	2.414	7.650	1.234
2020	0.179	1.567	0.364	2.018	1.854	2.348	7.665	1.150
2021	0.182	1.579	0.363	2.075	1.164	2.390	7.711	1.175

Source: Authors' calculation

The authors further divided the dataset into sub-samples to enable a more thorough understanding of the actual conditions in the countries under investigation (Table 4). First, the dataset was partitioned into two sub-samples, each of which related to a distinct group, as indicated by the mean FD value of 0.232. The countries categorized as Group 1a were those with FD values below the mean; those with FD values above the mean were classified as Group 2a. The following countries are included in Group 1a: Bangladesh, Bhutan, Cambodia, Kyrgyz Republic, Lao PDR, Myanmar, Nepal, Tajikistan, Timor-Leste, and Uzbekistan. Group 2a comprised India, Iran, Jordan, Lebanon, Mongolia, Pakistan, the Philippines, Sri Lanka, and Vietnam. The environmental degradation (ED_2a_H) in Group 2a is considerably greater than that in Group 1a (ED_1a_L), as illustrated in Figure 1. In lower-middle-income countries, financial development may stimulate business activities, investment, and energy consumption, which in turn exacerbates environmental degradation. Consequently, this result is consistent with these characteristics. In addition, Figure 1 indicates a general trend in which financial development is in accordance with environmental degradation, a finding that was observed in both groups.

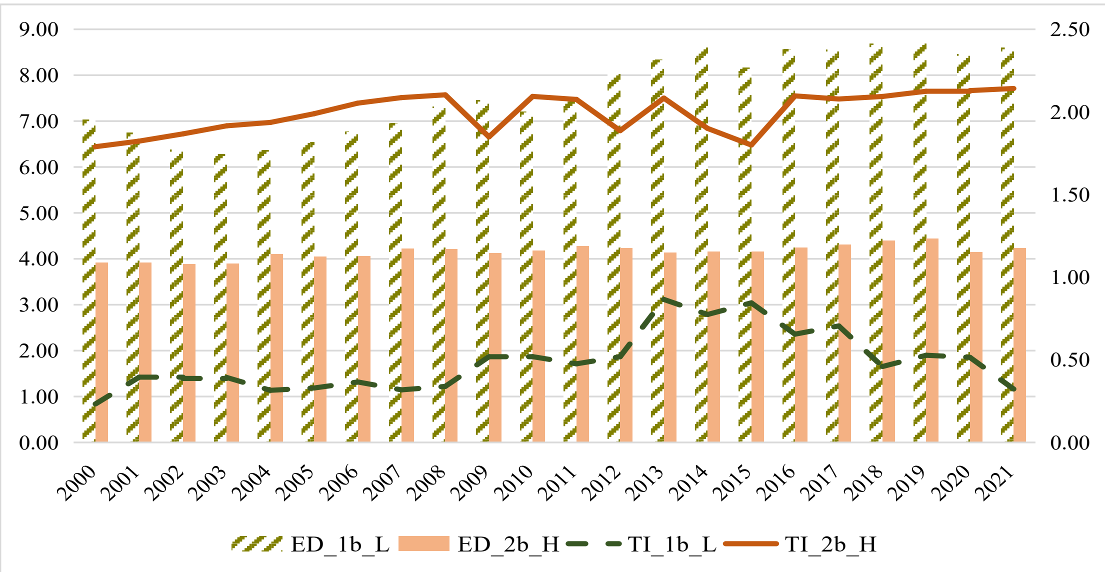
Figure 1. Mean values of financial development and environmental degradation in countries with above- and below-mean levels of financial development



Source: Authors' calculation

The authors subsequently designated the dataset to two sub-samples: Group 1b, which consisted of countries with TI values below the mean, and Group 2b, which consisted of countries with TI values above the mean, based on the mean value of TI of 4.333. Bhutan, Cambodia, Kyrgyz Republic, Lao PDR, Lebanon, Mongolia, Myanmar, Nepal, Tajikistan, and Timor-Leste comprise Group 1b. Group 2b comprises Bangladesh, India, Iran, Jordan, Pakistan, the Philippines, Sri Lanka, Uzbekistan, and Vietnam. The environmental degradation (ED_1b_L) in Group 1b is substantially higher than in Group 2b (ED_2b_H), as illustrated in Figure 2. A significant difference between the two groups is evident. This finding suggests that countries with lesser levels of technological innovation are more likely to experience greater environmental degradation, while those with higher levels of technological innovation tend to face less severe environmental challenges. This discovery underscores the critical role of technological innovation in the mitigation of environmental degradation in lower-middle-income countries.

Figure 2. Mean values of technological innovation and environmental degradation in countries with above- and below-mean levels of technological innovation



Source: Authors' calculation

4. 2. ESTIMATION RESULTS

First, the authors apply the Levin-Lin-Chu (LLC) suggested by Levin et al. (2002) to determine the stationarity of the variables. The results are presented in Table 5.

Table 5. Stationarity test

Levin-Lin-Chu unit-root test	Statistic	p-value	st difference
Null hypothesis: ED has a unit root	-1.440	0.075^{*}	d = 0
Null hypothesis: FD has a unit root	-2.532	0.006^{***}	d = 0
Null hypothesis: TI has a unit root	-5.300	0.000^{***}	d = 0
Null hypothesis: GG has a unit root	-2.056	0.020^{**}	d = 0
Null hypothesis: EG has a unit root	-6.409	0.000^{***}	d = 0
Null hypothesis: PG has a unit root	-1.879	0.030^{**}	d = 0
Note: $^{***}p \leq 0.01$; $^{**}p \leq 0.05$; $^{*}p \leq 0.1$.			

Source: Authors' calculation

Table 5 indicates that all the variables are stationary at level, i.e., I(0). Hence, these variables are used to estimate the model using the PVAR approach.

Table 6. Lag selection criteria

lag	CD	J	J pvalue	MBIC	MAIC	MQIC
1	0.9999992	110.187	0.423	-513.799	-105.813	-268.676
2	0.9999994	63.071	0.765	-352.920	-80.929	-189.505
3	0.9999989	22.544	0.961	-185.452	-49.456	-103.744
4	0.9999989	-	-	-	-	-

Source: Authors' calculation

Table 6 shows that the first-order PVAR model is preferred because it has the lowest MBIC, MAIC, and MQIC values. This selection is based on the optimal lag selection criterion proposed by (Andrews & Lu, 2001). Therefore, the authors proceed with estimating the model using the first-order PVAR approach.

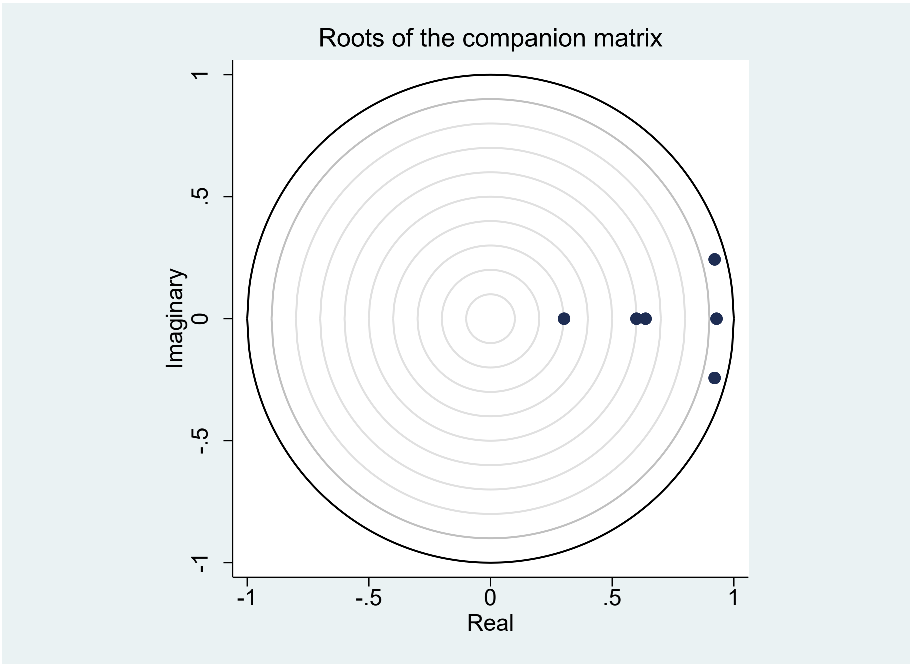
Table 7. Estimation results using the PVAR method

Variable	ED	FD	TI
	(1)	(2)	(3)
ED(-1)	0.902^{***} (0.000)	-0.031^{***} (0.000)	0.768^{**} (0.029)
FD(-1)	1.677^{***} (0.000)	1.138^{***} (0.000)	-0.907 (0.741)
TI(-1)	0.009 (0.178)	0.004^{***} (0.000)	0.339^{***} (0.000)
GG(-1)	0.013^{***} (0.000)	-0.001 (0.199)	0.016 (0.355)
EG(-1)	0.007^{**} (0.014)	-0.001 (0.660)	0.070^{***} (0.000)
PG(-1)	0.003 (0.595)	-0.003^{***} (0.009)	0.111^{**} (0.030)
Note: $^{***}p \leq 0.01$; $^{**}p \leq 0.05$.			

Source: Authors' calculation

The estimation results of the model using the first-order PVAR approach, presented in Table 7, reveal that environmental degradation (ED) is positively influenced by financial development (FD) with a one-period lag. Meanwhile, financial development is negatively affected by environmental degradation but positively influenced by technological innovation (TI) with a one-period lag. For technological innovation, it is positively affected by environmental degradation. These findings are fully consistent with the Granger causality test results in Table 8. It can be concluded that financial development directly affects environmental degradation, whereas technological innovation (TI) does not have a direct impact on environmental degradation but instead exerts an indirect effect through financial development (FD). Specifically, technological innovation can boost financial development, but it does not have any noticeable impact on lowering environmental degradation. Meanwhile, financial development may contribute to increased environmental degradation. On the other hand, environmental degradation may impede financial development in the lower-middle-income countries but simultaneously serve as a driver to enhance their technological innovation in finding optimal solutions that balance economic growth with environmental protection. Regarding the control variables, GDP growth can worsen environmental degradation. Meanwhile, economic globalization can foster technological innovation in these countries; however, it may also contribute to environmental degradation. Besides, a rising population may place a burden on the financial sector's development process but may also lead to an increase in the number of innovations and inventions within a country.

Figure 3. Eigenvalue stability condition



Source: Authors' calculation

Figure 3 shows that all the eigenvalues lie inside the unit circle. Therefore, the PVAR model satisfies the stability condition. Moreover, this result further supports the reliability of the estimated coefficients.

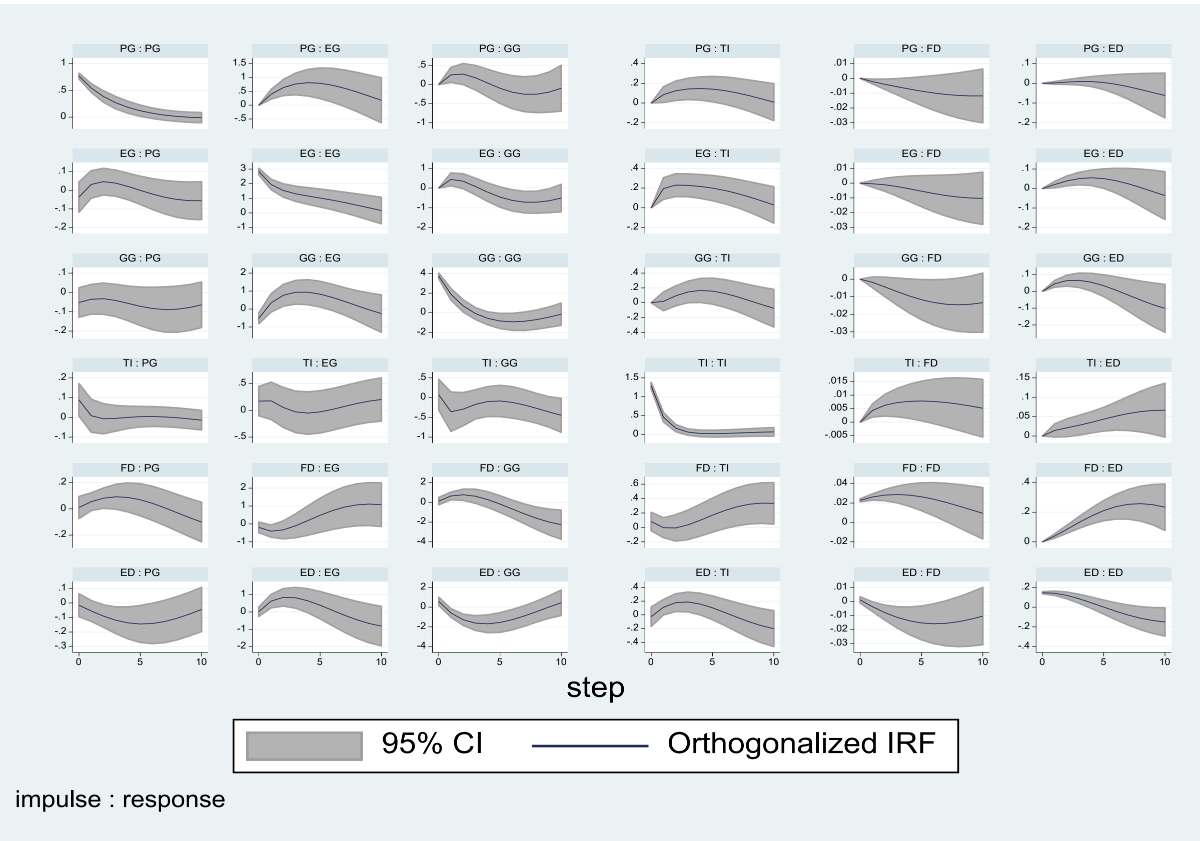
Table 8. Granger causality test results

Inferences of causality		Results	
H_1	FD → ED	25.376*** (0.000)	Yes
H_2	TI → ED	1.816 (0.178)	No
H_3	FD → TI	0.109 (0.741)	No
	TI → FD	16.590*** (0.000)	Yes
Note: *** $p \leq 0.01$			

Source: Authors' calculation

The Impulse Response Function (IRF) analysis results, presented in Figure 1, fully align with the findings in Table 7 and Table 8 while also demonstrating the impact of the variables in the long term. Specifically, Figure 4 shows that financial development worsens environmental degradation in both the short and long term. Meanwhile, technological innovation does not exhibit a significant effect on environmental degradation. Regarding the relationship between financial development and technological innovation, the latter promotes the former in both the short and long term, whereas the positive impact of the former on the latter is primarily observed in the long term. This indicates a close link between financial development and technological innovation. Furthermore, financial development directly influences environmental degradation by increasing it. However, technological innovation does not exert a direct impact on environmental degradation.

Figure 4. Impulse Response Function analysis results



Source: Authors' calculation

4. 3. DISCUSSION

The estimation results indicate that financial development can make environmental degradation worse in the lower-middle-income countries in Asia. Meanwhile, technological innovation has not yet demonstrated a significant effect in mitigating environmental degradation there. Furthermore, financial development and technological innovation are closely related, which could influence how each factor contributes to environmental degradation. This represents a novelty of this study compared to previous research.

The relationship between financial development and environmental degradation: The estimation results indicate that financial development increases environmental degradation in both the short and long term, thereby supporting Hypothesis H_1. This is consistent with previous studies by Danish et al. (2019), Saud et al. (2020), Ahmed et al. (2021), Kihombo et al. (2021), and Wijethunga et al. (2023). Moreover, it aligns with the endogenous growth (Aghion & Howitt, 1992), EKC hypothesis (Ling et al., 2022), and scale effect theories (Koçak & **Şarkgüneşi, 2018**). Accordingly, the findings fit with the initial stage of the EKC theory, which suggests financial development contributes to income growth but may also lead to environmental degradation (Ling et al., 2022). They also support the scale effect theory, which contends that financial development can expand production scale, thereby intensifying environmental degradation (Koçak & Şarkgüneşi, 2018). These findings align with the features of the lower-middle-income countries in Asia. Indeed, financial development is an essential measure for promoting business, investment, and even the expansion of industrial zones. However, this process also results in higher energy consumption, leading to more severe environmental degradation. Moreover, financial development facilitates greater access to financial resources, enhancing consumer purchasing power, which can negatively affect the environment, particularly when resource consumption rises. Thus, financial development can contribute to worsening environmental degradation in the lower-middle-income countries. In fact, although financial development is vital for fostering business and economic growth, these countries must also consider its environmental consequences.

The relationship between technological innovation and environmental degradation: The estimation results demonstrate that technological innovation has not exerted a significant effect on reducing environmental degradation in the lower-middle-income countries in Asia. This is implicit in the fact that most of these countries have limited levels of technological innovation. Moreover, the adoption of advanced technologies for environmental improvements has not been highlighted in these countries. Therefore, a challenge for these countries is to recognize the critical role of technological innovation, which is not only in boosting business and industrial growth but also in promoting modern, environmentally friendly technologies in order to reduce environmental degradation. These findings support the conclusions of Sabir and Gorus (2019), who examined South Asian countries, and Destek and Manga (2021), who analyzed emerging economies.

The relationship between financial development and technological innovation: The estimation results show that technological innovation fosters financial development in both the short and long term, while financial development plays an important role in encouraging technological innovation over the long run. Admittedly, there is a positive link between financial development and technological innovation, confirming the acceptance of Hypothesis H_3. This aligns with the endogenous growth theory, which posits that financial development and technological innovation are essential endogenous factors that affect environmental quality and sustainable development. Accordingly, financial development provides necessary financial resources to support technological innovation, which could help to lessen environmental degradation if it concentrates on eco-friendly technology and the economical use of energy resources (Shoaib et al., 2020). On the other hand, technological innovation can support financial development, particularly by applying advanced technologies to improve the quality of financial services, which is consistent with what has been found by (Jinqiao et al., 2022). Although the estimation results suggest that financial development has accelerated environmental degradation in the lower-middle-income countries in Asia, it could help control environmental degradation if it is effective in environmentally friendly industries, such as increasing credit supply for green projects. This possibility has been reported in previous studies (Adebayo et al., 2021; Baloch et al., 2021; Jinqiao et al., 2022). The positive nexus between financial development and technological innovation is evident in the lower-middle-income countries in Asia. However, leveraging the benefits of financial development and technological innovation to improve environmental quality remains inefficient in these economies.

The impact of the control variables on financial development, technological innovation, and environmental degradation: The estimation results confirm that GDP growth may intensify environmental degradation in the lower-middle-income countries in Asia. This supports prior research by Jianguo et al. (2022), Jinqiao et al. (2022), Fakher et al. (2023), and Dam et al. (2024). Furthermore, economic globalization can enhance technological innovation in these countries; however, it may also cause environmental degradation, affirming what Ullah et al. (2023) revealed. Also, rapid population growth may place a burden on developments of the financial sector, but it can increase the number of innovations.

5. CONCLUDING REMARKS

This study analyzes the impact of financial development and technological innovation on environmental degradation in the lower-middle-income Asian countries. Notably, the authors examine the causal relationship between financial development and technological innovation when considering their effects on environmental degradation, which is a key contribution of this study. Using the PVAR method, the estimation results indicate that financial development may worsen environmental degradation in both the short and long term. However, technological innovation has not demonstrated a significant impact on mitigating environmental degradation in these countries. A noteworthy finding is the positive link between financial development and technological innovation, concluding that these two factors may complement each other in the development process. Despite this, these countries have not fully leveraged the benefits of financial development and technological innovation to address issues of environmental degradation. These findings highlight the necessity of developing appropriate policies to maximize the advantages of financial development and technological innovation in reducing environmental degradation. Furthermore, they indicate that GDP growth and economic globalization also exert a significant impact on environmental degradation in these countries.

The findings provide a reliable foundation for the lower-middle-income Asian countries to identify proper strategies for promoting financial development coupled with technological innovation, ultimately aiming to minimize environmental degradation. To achieve this goal, these countries must implement a comprehensive set of policies covering financial development, technological innovation, and other relevant areas such as GDP growth, economic globalization, and population growth.

Regarding financial development, these countries must make greater efforts to establish an inclusive financial system that creates financial resources to support GDP growth together with improving environmental quality. Specifically, the financial system should prioritise capital allocation to environmentally friendly projects. Economic activities and investments can be stimulated by financial development; however, it can also have a negative impact on the environment, especially in countries where economic growth is often prioritised over sustainability. For instance, Figure 1 demonstrates that countries with financial development levels that exceed the average are more likely to experience severe environmental degradation than those with lower levels. Therefore, the financial system's role in securing funding for environmentally responsible and sustainable projects is of the utmost importance, particularly for nations with relatively high levels of financial development, including India, Iran, Jordan, Lebanon, Mongolia, Pakistan, the Philippines, Sri Lanka, and Vietnam. Conversely, the remaining countries in the sample – Bangladesh, Bhutan, Cambodia, Kyrgyz Republic, Lao PDR, Myanmar, Nepal, Tajikistan, Timor-Leste, and Uzbekistan – display relatively low levels of environmental degradation and financial development. The promotion of financial development in these countries should be emphasised in conjunction with sustainability objectives.

To promote technological innovation, these nations should emphasize enhancing innovation capacities, specifically targeting the development of technology aimed at reducing environmental damage. Furthermore, to foster innovation in the financial sector, technology must be integrated into the improvement of financial services. Research results suggest that nations with reduced technological innovation experience significantly more severe environmental degradation. This underscores the importance of technology-driven solutions that can help advance sustainable development goals. Bhutan, Cambodia, Kyrgyz Republic, Lao PDR, Lebanon, Mongolia, Myanmar, Nepal, Tajikistan, and Timor-Leste are all countries in Group 1b that are growing more vulnerable to environmental degradation, while their levels of technological innovation are relatively low. These countries must increase their technological innovation capacity in order to achieve sustainable development. To achieve this, it is essential to prioritize the cultivation of indigenous innovation ecosystems through the enhancement of international collaboration to enable technology transfer. In contrast, nations in Group 2b, such as Bangladesh, India, Iran, Jordan, Pakistan, the Philippines, Sri Lanka, Uzbekistan, and Vietnam, have achieved significant advancements in technological innovation. The commercialization of sustainable technologies must be accelerated while fostering innovation in these nations. This will allow them to fully exploit the benefits of innovation in achieving long-term development goals and environmental sustainability.

Also, these countries should enhance economic growth and globalization by utilizing the advantages of globalization and adopting suitable measures to prevent environmental damage. Furthermore, population growth should be accompanied by improvements in human capital quality to ensure that excessive population expansion does not become an obstacle to sustainable development.

This study has successfully looked at how financial development and technological innovation affect environmental damage in lower-middle-income Asian countries, while also exploring how financial development and technological innovation are related to each other. However, it has certain limitations. Firstly, the data limit has prevented the authors from estimating the model for individual countries and from expanding the dataset to include other regions. Moreover, this study focuses on the lower-middle-income Asian countries to suggest policy implications for this group. In fact, the impact of financial development and technological innovation on environmental degradation may vary across different country groups, such as upper-middle-income or high-income countries. However, this issue has not been addressed in this study. Next, with regard to measuring financial development, this study uses a composite index. This approach has the advantage of capturing the multidimensional nature of financial development. However, it has certain limitations, especially the inability to distinguish specific aspects of financial development in detail. With respect to technological innovation, this study uses the total number of patent applications (including both residents and non-residents) as a proxy. While this indicator effectively reflects actual innovation outcomes in each country, it has limitations in that it does not capture input factors such as R&D expenditure, nor does it reflect the extent of technology adoption, such as ICT indicators. Finally, due to data limitations, the study is unable to consider the role of country-specific environmental policies, which could have helped further contextualise and clarify the empirical findings. Future studies can address these limitations to develop more intriguing research directions.

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REFERENCES

Abrigo, M. R. M., & Love, I. (2016). Estimation of Panel Vector Autoregression in Stata. *The Stata Journal: Promoting Communications on Statistics and Stata*, 16(3), 778–804. https://doi.org/10.1177/1536867X1601600314

Adams, S., Klobodu, E. K. M., & Apio, A. (2018). Renewable and non-renewable energy, regime type and economic growth. *Renewable Energy*, 125, 755–767. https://doi.org/10.1016/j.renene.2018.02.135

Adebayo, T. S., Akinsola, G. D., Bekun, F. V., Osemeahon, O. S., & Sarkodie, S. A. (2021). Mitigating human-induced emissions in Argentina: Role of renewables, income, globalization, and financial development. *Environmental Science and Pollution Research*, 28(47), 67764–67778. https://doi.org/10.1007/s11356-021-14830-5

Aghion, P., & Howitt, P. (1992). A model of growth through creative destruction. *Econometrica*, 60(2), 323–351. https://doi.org/10.2307/2951599

Ahmed, Z., Asghar, M. M., Malik, M. N., & Nawaz, K. (2020). Moving towards a sustainable environment: The dynamic linkage between natural resources, human capital, urbanization, economic growth, and ecological footprint in China. *Resources Policy*, 67, 101677. https://doi.org/10.1016/j.resourpol.2020.101677

Ahmed, Z., Wang, Z., Mahmood, F., Hafeez, M., & Ali, N. (2019). Does globalization increase the ecological footprint? Empirical evidence from Malaysia. *Environmental Science and Pollution Research*, 26(18), 18565–18582. https://doi.org/10.1007/s11356-019-05224-9

Ahmed, Z., Zhang, B., & Cary, M. (2021). Linking economic globalization, economic growth, financial development, and ecological footprint: Evidence from symmetric and asymmetric ARDL. *Ecological Indicators*, 121, 107060. https://doi.org/10.1016/j.ecolind.2020.107060

Andrews, D. W. K., & Lu, B. (2001). Consistent model and moment selection procedures for GMM estimation with application to dynamic panel data models. *Journal of Econometrics*, 101(1), 123–164. https://doi.org/10.1016/S0304-4076(00)00077-4

Asongu, S. A., Le Roux, S., & Biekpe, N. (2018). Enhancing ICT for environmental sustainability in sub-Saharan Africa. *Technological Forecasting and Social Change*, 127, 209–216. https://doi.org/10.1016/j.techfore.2017.09.022

Baigorri, B., Montañés, A., & Simón-Fernández, M.-B. (2025). The influence of the great recession on the relationship between ecological footprint, renewable energy and economic growth. *Environmental and Sustainability Indicators*, 25, 100556. https://doi.org/10.1016/j.indic.2024.100556

Baloch, M. A., Ozturk, I., Bekun, F. V., & Khan, D. (2021). Modeling the dynamic linkage between financial development, energy innovation, and environmental quality: Does globalization matter? *Business Strategy and the Environment*, 30(1), 176–184. https://doi.org/10.1002/bse.2615

Bekun, F. V., Alola, A. A., Gyamfi, B. A., & Ampomah, A. B. (2021). The environmental aspects of conventional and clean energy policy in sub-Saharan Africa: Is N-shaped hypothesis valid? *Environmental Science and Pollution Research*, 28(47), 66695–66708. https://doi.org/10.1007/s11356-021-14758-w

Botev, J., Égert, B., & Jawadi, F. (2019). The nonlinear relationship between economic growth and financial development: Evidence from developing, emerging and advanced economies. *International Economics*, 160, 3–13. https://doi.org/10.1016/j.inteco.2019.06.004

Brown, J. R., Martinsson, G., & Petersen, B. C. (2012). Do financing constraints matter for R&D? *European Economic Review*, 56(8), 1512–1529. https://doi.org/10.1016/j.euroecorev.2012.07.007

Bui, N. T., & Doan, T.-T. T. (2024). Foreign direct investment and green GDP: The thresholds of financial development for economic policies. *Cogent Economics & Finance*, 12(1), 2437011. https://doi.org/10.1080/23322039.2024.2437011

Chang, S.-C. (2015). Effects of financial developments and income on energy consumption. *International Review of Economics & Finance*, 35, 28–44. https://doi.org/10.1016/j.iref.2014.08.011

Cherif, M., & Dreger, C. (2016). Institutional determinants of financial development in MENA countries. *Review of Development Economics*, 20(3), 670–680. https://doi.org/10.1111/rode.12192

Dam, M. M., Kaya, F., & Bekun, F. V. (2024). How does technological innovation affect the ecological footprint? Evidence from E-7 countries in the background of the SDGs. *Journal of Cleaner Production*, 443, 141020. https://doi.org/10.1016/j.jclepro.2024.141020

Danish, Baloch, M. A., Mahmood, N., & Zhang, J. W. (2019). Effect of natural resources, renewable energy and economic development on CO2 emissions in BRICS countries. *Science of The Total Environment*, 678, 632–638. https://doi.org/10.1016/j.scitotenv.2019.05.028

Destek, M. A., & Manga, M. (2021). Technological innovation, financialization, and ecological footprint: evidence from BEM economies. *Environmental Science and Pollution Research*, 28(17), 21991–22001. https://doi.org/10.1007/s11356-020-11845-2

Elhassan, T. (2025). Green Technology Innovation, Green Financing, and Economic Growth in G7 Countries: Implications for Environmental Sustainability. *Economics - innovative and economics research journal*, 13(1), 69–91. https://doi.org/10.2478/eoik-2025-0023

Ercan, H., Savranlar, B., Polat, M. A., Yıgıt, Y., & Aslan, A. (2024). The impact of technological innovations on the environmental Kuznets curve: Evidence from EU-27. *Environmental Science and Pollution Research*, 31(13), 19886–19903. https://doi.org/10.1007/s11356-024-32303-3

Fakher, H. A., Ahmed, Z., Acheampong, A. O., & Nathaniel, S. P. (2023). Renewable energy, nonrenewable energy, and environmental quality nexus: An investigation of the N-shaped Environmental Kuznets Curve based on six environmental indicators. *Energy*, 263, 125660. https://doi.org/10.1016/j.energy.2022.125660

Fakher, H. A., Panahi, M., Emami, K., Peykarjou, K., & Zeraatkish, S. Y. (2021). Investigating marginal effect of economic growth on environmental quality based on six environmental indicators: Does financial development have a determinative role in strengthening or weakening this effect? *Environmental Science and Pollution Research*, 28(38), 53679–53699. https://doi.org/10.1007/s11356-021-14470-9

Ganda, F. (2020). Effect of foreign direct investment, financial development, and economic growth on environmental quality in OECD economies using panel quantile regressions. *Environmental Quality Management*, 30(2), 89–118. https://doi.org/10.1002/tqem.21715

Godil, D. I., Yu, Z., Sharif, A., Usman, R., & Khan, S. A. R. (2021). Investigate the role of technology innovation and renewable energy in reducing transport sector CO_2 emission in China: A path toward sustainable development. *Sustainable Development*, 29(4), 694–707. https://doi.org/10.1002/sd.2167

Grossman, G. M., & Helpman, E. (1991). Quality ladders in the theory of growth. *The Review of Economic Studies*, 58(1), 43–61. https://doi.org/10.2307/2298044

Jianguo, D., Ali, K., Alnori, F., & Ullah, S. (2022). The nexus of financial development, technological innovation, institutional quality, and environmental quality: Evidence from OECD economies. *Environmental Science and Pollution Research*, 29(38), 58179–58200. https://doi.org/10.1007/s11356-022-19763-1

Jinqiao, L., Maneengam, A., Saleem, F., & Mukarram, S. S. (2022). Investigating the role of financial development and technology innovation in climate change: Evidence from emerging seven countries. *Economic Research-Ekonomska Istraživanja*, 35(1), 3940–3960. https://doi.org/10.1080/1331677X.2021.2007152

Ke, H., Yang, W., Liu, X., & Fan, F. (2020). Does innovation efficiency suppress the ecological footprint? Empirical evidence from 280 Chinese cities. *International Journal of Environmental Research and Public Health*, 17(18), 6826. https://doi.org/10.3390/ijerph17186826

Khrisat, M. & Alqadi, Z. (2023). Performance Evaluation of ANN Models for Prediction. Acadlore *Transactions on AI and Machine Learning,* 2(1), 13-20. https://doi.org/10.56578/ataiml020102

Kihombo, S., Ahmed, Z., Chen, S., Adebayo, T. S., & Kirikkaleli, D. (2021). Linking financial development, economic growth, and ecological footprint: What is the role of technological innovation? *Environmental Science and Pollution Research*, 28(43), 61235–61245. https://doi.org/10.1007/s11356-021-14993-1

Koçak, E., & Şarkgüneşi, A. (2018). The impact of foreign direct investment on CO_2 emissions in Turkey: New evidence from cointegration and bootstrap causality analysis. *Environmental Science and Pollution Research*, 25(1), 790–804. https://doi.org/10.1007/s11356-017-0468-2

Koondhar, M. A., Shahbaz, M., Ozturk, I., Randhawa, A. A., & Kong, R. (2021). Revisiting the relationship between carbon emission, renewable energy consumption, forestry, and agricultural financial development for China. *Environmental Science and Pollution Research*, 28(33), 45459–45473. https://doi.org/10.1007/s11356-021-13606-1

Kumail, T., Ali, W., Sadiq, F., Wu, D., & Aburumman, A. (2020). Dynamic linkages between tourism, technology and CO_2 emissions in Pakistan. *Anatolia*, 31(3), 436–448. https://doi.org/10.1080/13032917.2020.1742169

Levin, A., Lin, C.-F., & James Chu, C.-S. (2002). Unit root tests in panel data: Asymptotic and finite-sample properties. *Journal of Econometrics*, 108(1), 1–24. https://doi.org/10.1016/S0304-4076(01)00098-7

Li, R., Wang, Q., Liu, Y., & Jiang, R. (2021). Per-capita carbon emissions in 147 countries: The effect of economic, energy, social, and trade structural changes. *Sustainable Production and Consumption*, 27, 1149–1164. https://doi.org/10.1016/j.spc.2021.02.031

Ling, G., Razzaq, A., Guo, Y., Fatima, T., & Shahzad, F. (2022). Asymmetric and time-varying linkages between carbon emissions, globalization, natural resources and financial development in China. *Environment, Development and Sustainability*, 24(5), 6702–6730. https://doi.org/10.1007/s10668-021-01724-2

Luo, R., Ullah, S., & Ali, K. (2021). Pathway towards sustainability in selected Asian countries: Influence of green investment, technology innovations, and economic growth on CO_2 Emission. *Sustainability*, 13(22), 12873. https://doi.org/10.3390/su132212873

Mahmood, H., Alkhateeb, T. T. Y., & Furqan, M. (2020). Exports, imports, foreign direct investment and CO_2 emissions in North Africa: Spatial analysis. *Energy Reports*, 6, 2403–2409. https://doi.org/10.1016/j.egyr.2020.08.038

Mensah, C. N., Long, X., Boamah, K. B., Bediako, I. A., Dauda, L., & Salman, M. (2018). The effect of innovation on CO_2 emissions of OCED countries from 1990 to 2014. *Environmental Science and Pollution Research*, 25(29), 29678–29698. https://doi.org/10.1007/s11356-018-2968-0

Moraliyska, M. (2023). Measuring the Justness of the European Green Transition. *Collection of papers new economy,* 1, 30-41. https://doi.org/10.61432/CPNE0101030m

Nathaniel, S. P., Murshed, M., & Bassim, M. (2021). The nexus between economic growth, energy use, international trade and ecological footprints: The role of environmental regulations in N11 countries. *Energy, Ecology and Environment*, 6(6), 496–512. https://doi.org/10.1007/s40974-020-00205-y

Ozcan, B., & Apergis, N. (2018). The impact of internet use on air pollution: Evidence from emerging countries. *Environmental Science and Pollution Research*, 25(5), 4174–4189. https://doi.org/10.1007/s11356-017-0825-1

Pan, D., Chen, C., Grubb, M., & Wang, Y. (2021). Financial policy, green transition and recovery after the COVID-19. *SSRN Electronic Journal*, 1–49. https://doi.org/10.2139/ssrn.3719695

Prempeh, K. B. (2023). The impact of financial development on renewable energy consumption: New insights from Ghana. *Future Business Journal*, 9(1), 6. https://doi.org/10.1186/s43093-023-00183-7

Rafique, M. Z., Li, Y., Larik, A. R., & Monaheng, M. P. (2020). The effects of FDI, technological innovation, and financial development on CO_2 emissions: Evidence from the BRICS countries. *Environmental Science and Pollution Research*, 27(19), 23899–23913. https://doi.org/10.1007/s11356-020-08715-2

Razzaq, A., An, H., & Delpachitra, S. (2021). Does technology gap increase FDI spillovers on productivity growth? Evidence from Chinese outward FDI in Belt and Road host countries. *Technological Forecasting and Social Change*, 172, 121050. https://doi.org/10.1016/j.techfore.2021.121050

Romer, P. M. (1990). Endogenous technological change. *Journal of Political Economy*, 98(5), S71–S102. https://www.jstor.org/stable/2937632

Rutendo Magwedere, M., & Marozva, G. (2025). Inequality and Informal Economy: The Moderating Role of Financial Technology. *Economics - innovative and economics research journal,* 13(1), 197–211. https://doi.org/10.2478/eoik-2025-0004

Saadaoui, H., & Chtourou, N. (2023). Do institutional quality, financial development, and economic growth improve renewable energy transition? Some evidence from Tunisia. *Journal of the Knowledge Economy*, 14(3), 2927–2958. https://doi.org/10.1007/s13132-022-00999-8

Sabir, S., & Gorus, M. S. (2019). The impact of globalization on ecological footprint: Empirical evidence from the South Asian countries. *Environmental Science and Pollution Research*, 26(32), 33387–33398. https://doi.org/10.1007/s11356-019-06458-3

Sadorsky, P. (2011). Financial development and energy consumption in Central and Eastern European frontier economies. *Energy Policy*, 39(2), 999–1006. https://doi.org/10.1016/j.enpol.2010.11.034

Saidi, K., & Mbarek, M. Ben. (2017). The impact of income, trade, urbanization, and financial development on CO_2 emissions in 19 emerging economies. *Environmental Science and Pollution Research*, 24(14), 12748–12757. https://doi.org/10.1007/s11356-016-6303-3

Saud, S., Chen, S., Haseeb, A., & Sumayya. (2020). The role of financial development and globalization in the environment: Accounting ecological footprint indicators for selected one-belt-one-road initiative countries. *Journal of Cleaner Production*, 250, 119518. https://doi.org/10.1016/j.jclepro.2019.119518

Socotar, D. L., & Gabor, M. R. (2024). The Effect of Renewable Obligations on Electricity Prices - Estimates for the UK. *Collection of papers new economy,* 2. 15-29. https://doi.org/10.61432/CPNE0201015d

Shahbaz, M., Solarin, S. A., Mahmood, H., & Arouri, M. (2013). Does financial development reduce CO2 emissions in Malaysian economy? A time series analysis. *Economic Modelling*, 35, 145–152. https://doi.org/10.1016/j.econmod.2013.06.037

Shi, L., Li, T. T., & Meng, Y. (2024). Urban Ecological Compensation Through Water Resource Ecological Footprint. *Opportunities and Challenges in Sustainability,* 3(3), 158-167. https://doi.org/10.56578/ocs030302

Shoaib, H. M., Rafique, M. Z., Nadeem, A. M., & Huang, S. (2020). Impact of financial development on CO_2 emissions: A comparative analysis of developing countries (D8) and developed countries (G8). *Environmental Science and Pollution Research*, 27(11), 12461–12475. https://doi.org/10.1007/s11356-019-06680-z

Solarin, S. A., Nathaniel, S. P., Bekun, F. V., Okunola, A. M., & Alhassan, A. (2021). Towards achieving environmental sustainability: Environmental quality versus economic growth in a developing economy on ecological footprint via dynamic simulations of ARDL. *Environmental Science and Pollution Research*, 28(14), 17942–17959. https://doi.org/10.1007/s11356-020-11637-8

Tamazian, A., & Rao, B. B. (2010). Do economic, financial and institutional developments matter for environmental degradation? Evidence from transitional economies. *Energy Economics*, 32(1), 137–145. https://doi.org/10.1016/j.eneco.2009.04.004

Tang, C. F., & Tan, B. W. (2015). The impact of energy consumption, income and foreign direct investment on carbon dioxide emissions in Vietnam. *Energy*, 79, 447–454. https://doi.org/10.1016/j.energy.2014.11.033

Uddin, G. A., Salahuddin, M., Alam, K., & Gow, J. (2017). Ecological footprint and real income: Panel data evidence from the 27 highest emitting countries. *Ecological Indicators*, 77, 166–175. https://doi.org/10.1016/j.ecolind.2017.01.003

Ullah, S., Adebayo, T. S., Irfan, M., & Abbas, S. (2023). Environmental quality and energy transition prospects for G-7 economies: The prominence of environment-related ICT innovations, financial and human development. *Journal of Environmental Management*, 342, 118120. https://doi.org/10.1016/j.jenvman.2023.118120

Usman, M., & Hammar, N. (2021). Dynamic relationship between technological innovations, financial development, renewable energy, and ecological footprint: Fresh insights based on the STIRPAT model for Asia Pacific Economic Cooperation countries. *Environmental Science and Pollution Research*, 28(12), 15519–15536. https://doi.org/10.1007/s11356-020-11640-z

Wang, D., Yu, W. Y., Ouyang, R. K., & Meng, Q. T. (2024). Unveiling the Mechanisms and Spatial Spillovers of Digital Finance in Enhancing Urban Green Efficiency. *Journal of Organizations, Technology and Entrepreneurship,* 2(4), 221-236. https://doi.org/10.56578/jote020403

Wijethunga, A. W. G. C., Rahman, M. M., & Dayaratne, D. A. I. (2023). The effect of financial development on environmental quality: A developing country evidence. *Environmental Science and Pollution Research*, 30(58), 121239–121252. https://doi.org/10.1007/s11356-023-30844-7

Xu, Z., Baloch, M. A., Danish, Meng, F., Zhang, J., & Mahmood, Z. (2018). Nexus between financial development and CO_2 emissions in Saudi Arabia: Analyzing the role of globalization. *Environmental Science and Pollution Research*, 25(28), 28378–28390. https://doi.org/10.1007/s11356-018-2876-3

Yuxiang, K., & Chen, Z. (2011). Financial development and environmental performance: Evidence from China. *Environment and Development Economics*, 16(1), 93–111. https://doi.org/10.1017/S1355770X10000422

Zameer, H., Wang, Y., & Yasmeen, H. (2019). Transformation of firm innovation activities into brand effect. *Marketing Intelligence & Planning*, 37(2), 226–240. https://doi.org/10.1108/MIP-05-2018-0176

Zameer, H., Yasmeen, H., Zafar, M. W., Waheed, A., & Sinha, A. (2020). Analyzing the association between innovation, economic growth, and environment: Divulging the importance of FDI and trade openness in India. *Environmental Science and Pollution Research*, 27(23), 29539–29553. https://doi.org/10.1007/s11356-020-09112-5

Zhang, C., & Liu, C. (2015). The impact of ICT industry on CO_2 emissions: A regional analysis in China. *Renewable and Sustainable Energy Reviews*, 44, 12–19. https://doi.org/10.1016/j.rser.2014.12.011

Zhou, X., Wang, L., & Du, J. (2021). Institutional environment and green economic growth in China. *Complexity*, 2021(1), 6646255. https://doi.org/10.1155/2021/6646255