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**Article**

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# Accelerating innovation in industrialized countries: how relevant is the interaction between financial development and environmental factors?

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**ABSTRACT**

The impact of countries' levels of financial sector development in influencing innovation and environmental quality cannot be overemphasized. However, studies on the tripartite relationships among financial sector development-innovation-environmental quality have produced mixed results, necessitating further research. This study, therefore, aims to investigate the impact of financial sector development on innovation and examine how financial sector development moderates the impact of environmental factors in influencing innovation. Relying on panel data spanning 1991–2014 for 27 selected industrialized countries, findings from the system generalized method of moment (GMM) suggest that higher financial development robustly increases innovation. Further evidence also shows that while higher energy consumption, renewable energy, and carbon dioxide emissions spur innovation, increases in ecological footprint lower innovations. However, a well-developed financial sector dampens the negative impact of ecological footprint on innovation while propelling the innovation-enhancing effect of carbon dioxide emissions and energy consumption with no apparent impact on renewable energy. A key implication of the findings is that financial development has a far more significant effect on innovation in countries with high environmental degradation and energy consumption.

**IMPACT STATEMENT**

In addition to examining to the effect of financial sector development on innovation, this study examines how financial sector development mediate the impact of environmental factors in influencing innovation in industrialized countries. We find that higher financial development and ecological footprint individually promote increases and decreases innovation respectively. However, a well-developed financial sector reduces the negative effect of ecological footprint on innovation. This study is significant and makes a case for countries to develop their financial sectors as a way of curbing environmental pollution.

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## 1. Introduction

All over the world, innovation has been recognized as one of the critical ingredients to spur economic development. The 2022 Global Innovation Index shows that Switzerland, the United States, Sweden, the United Kingdom, and the Netherlands are the five most innovative countries.[1] Primarily, a country's innovation set-up, as given in its Research and Development (R&D) activities, influences the extent of its innovation (Edquist, 2011; Islam, 2009; Pegkas et al., 2019).

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Many studies have, in recent times, attempted to identify determinants of innovation. Of particular importance in empirical research is the contribution of financial sector development in supporting innovation both as an outcome and as a means of promoting economic expansion. Low et al. (2018) report that well-developed financial markets provide the needed efficient financial services to ensure higher innovation. Aghion et al. (2018) also show that improved financial sectors spur innovation by ameliorating information asymmetry and agency problems while supporting productive firms to participate in activities that ensure higher innovation.

In the last few decades, many studies have examined the determinants of innovation, particularly the role of financial development, albeit inconclusive results (Low et al., 2018; Meierrieks, 2014; Pradhan et al., 2016). To deal with these inconsistencies, some authors have concentrated on the mediation role of countries' institutions (Ho et al., 2018; Law et al., 2018) and human capital (Peng et al., 2020) in the innovation–financial development relationship.

What has hitherto not been studied in the existing research efforts is the role of environmental factors in innovation. Meanwhile, issues around climate change have gained traction following the extent of global environmental degradation, particularly in industrialized countries. This study focused on industrialized countries because Climate Transparency (2019) reports that the Organization for Economic Cooperation and Development (OECD) and the G20 countries, which are heavily industrialized, are the world's leading polluters, emitting 80% of total greenhouse gas globally. Finding innovative ways to reduce degradation is one of the major concerns of these countries. However, how degradation and energy intensity influence their levels of innovation is not empirically well documented. More tellingly, given the relatively improved nature of the financial sector in industrialized countries, examining how it interacts with environmental factors in influencing innovation deserves nuanced analysis. Unfortunately, studies analyzing the tripartite relations between financial development, environmental quality, and innovations are scanty. More so, the extant studies in the literature have produced mixed results, which leaves policymakers uncertain about the exact policy prescriptions to pursue regarding the linkages involving financial development, environment, and innovation.

The article has two objectives. The first objective seeks to investigate the impact of financial development on innovation. The second objective examines how financial development affects the relationship between environmental factors and innovation. To our knowledge, only Pham's (2019) and Li and Shao (2023) studies are close to our present study. Using 22 OECD countries and invoking the fixed effects Poisson estimator, Pham (2019) finds that improved financial development significantly enhances innovation. It was further observed that the overall impact of financial development depends on carbon dioxide intensity. Apart from using a narrow focus on $CO_2$ emissions and relying on dummy variables to denote polluting countries, a major weakness of the study is its inability to control for potential endogeneities eminent in their panel dataset. Furthermore, the study is unable to show the conditional effects of financial development at the various levels of environmental factors. More recently, Li and Shao (2023) examined the role of financial development and environmental policy stringency in promoting renewable energy innovation in 37 OECD countries using the non-linear panel threshold model. The authors established a non-linear positive effect between financial market development and renewable energy innovation in mid- and high-level regimes, suggesting that a mature financial market fosters renewable energy innovation. On the other hand, it was realized that stringent environmental policy enhances renewable innovation. It is important to mention that the study of Li and Shao (2023) relied on the narrow measure of financial development (financial market development index), focused on environmental regulation, and failed to address the endogeneity issue in the environment-financial development-innovation nexus. Our study is not interested in environmental regulation but in how environmental degradation and energy intensity affect innovation. Additionally, we are interested in the net effect of the interaction of financial development and environmental factors on innovation, which extant studies in the literature are yet to analyse.

In addition to correcting the weaknesses of Pham's (2019) and Li and Shao (2023) study, we extend the coverage to include several other important environmental factors and more comprehensive measures of financial development. Our work hinges on the National Innovation Capacity (NIC) theoretical model, which focuses on wide-ranging factors influencing innovation (Furman et al., 2002; Krammer, 2009). The national innovation systems framework is suggestive of the fact that country-specific characteristics matter in explaining innovation. Innovation is expected to be higher, especially in countries with well-developed

financial markets where funding options are available, as this enhances research-based activities. In this essence, we set two hypotheses: first, the extent of innovation is not only determined by previous levels of financial development but also by the previous levels of environmental degradation, energy consumption and renewable energy. We argue here that the impact of environmental factors is not immediate as they have lag effects. Thus, present innovation is conditioned on previous financial development and levels of environmental factors. For our second hypothesis, we argue that the financial systems of countries with very high innovation can exert counteractive effects on environmental factors, and these together play a significant role in influencing innovation. The role of financial systems in addressing environmental pollution ensures that financial resources are available for technological innovation and financing research and development activities (Sadorsky, 2010). In this case, higher degradation and energy consumption effects are expected to be countered by the well-developed financial sector. Thus, the financial development-innovation link will vary according to the level of environmental factors.

This study adds depth to the literature in at least three ways. First, this study deviates from using $CO_2$ emissions as the measure of degradation by relying on an all-encompassing indicator of environmental pollution known as ecological footprint. This measure reflects the different dimensions of pollution.[2] Second, we also rely on more comprehensive and multidimensional measure of the financial sector. This measure is based on the market and bank indicators of the financial system, which are mostly relevant for the countries in the industrialized region, given the nature of their financial sectors. Admittedly, the single-based measures of financial development are far from fully capturing the entire financial system. Third, we unearth the conditional effects of financial development at the different levels of countries' environmental factors. Through this, we are able to show whether financial development magnifies or dampens the impact of environmental factors on innovation. Methodology, we rely on an estimation approach that controls for potential endogeneity and reverse causality that earlier studies failed to engage. Thus, our study is able to produce consistent and efficient estimates.

Our findings show that improved financial development enhances innovation in industrialized countries and dampens the negative effect of an ecological footprint on innovation while propelling the innovation-enhancing effect of $CO_2$ emissions and energy consumption with no apparent effect on renewable energy. In the section that follows, we present the literature review. Section 3 focuses on the discussion of the methodology, while Section 4 analyzes the results. The concluding remarks are highlighted in Section 5.

## 2. Literature review

### *2.1 Theoretical literature review*

This study is motivated by economic theories emphasising the role of finance and environmental standards in fostering innovation activities. Schumpeter's (1912) theory of economic development is one of the foremost studies that emphasize the relationship between finance and innovation. He argued that financial institutions are critical in advancing a country's innovation by evaluating and funding entrepreneurs in their initiation of innovation activities. Building on this theoretical argument, King and Levine (1993) noted that stimulating innovation depends on a well-developed financial system. In their view, a more developed financial system can enhance innovation scope and efficiency through a range of financial services such as 'evaluating entrepreneurs, pooling resources, diversifying risk, and valuing the expected profits from innovative activities'. Levine (2005) also stressed the importance of a financial system positively influencing innovation via savings accumulation. The author emphasized that a more effective financial system can lead to better savings mobilization and resource allocation, spurring technological innovation. In another study, Tadesse (2005) theoretically shows that industries located in countries with improved financial development enjoy significant economies of scale by lowering their real costs, thereby releasing more funds for innovative technologies. The author further emphasises that higher financial development encourages innovation because the uptake of new technologies requires a huge capital outlay provided by the financial sector. Similarly, Dabla-Norris et al. (2012) argue that the financial sector's role in driving productivity and innovation depends on its ability to efficiently and optimally distribute capital.

As for the relationship between environmental quality and innovation, Porter's hypothesis, inspired by Porter (1991) and Porter and van der Linde (1995), provides the theoretical background for understanding

the nexus. This hypothesis claims that 'properly designed environmental standards can trigger innovation that may partially or more than fully offset the costs of complying with them.' According to the authors, firms that increase the environmental efficiency of resources may spur innovation, which enhances environmental respect and helps improve production methods and product quality. This has a long-term advantage in generating competitive advantage, bolstering organisations' capacity for innovation. For this to happen, the authors highlighted the following three principles to guide the design of environmental policies to promote innovation. First, there is the need to maximize the potential for innovation by letting the industry, not the environmental standard-setting organisations, determine the approach to innovation. Second, there is no need to stifle any particular technology when ensuring regulations foster continuous improvement. Third, there should be little room for doubt at any stage of the regulatory process. Following these principles can lead to environmental policies fostering innovation outcomes. In explaining this effect, Perman et al. (2011) emphasize that limiting the utilization of technologies causing pollution or requiring the use of cleaner technologies raises the implicit emissions costs for business, which stimulates innovation.

Taken together, these arguments provide the theoretical basis for this study on the dynamic linkage between financial development, environmental quality, and innovation. In the next section, we review extant empirical literature that has bearings on the subject under study.

## 2.2 Empirical literature review

### 2.2.1 Relationship between financial development and innovation

While the theoretical literature on the relationship between financial development and innovation is largely conclusive, empirical evidence on the nexus is mixed. By utilizing data from 15 developing countries, Kapidani and Luci (2019) study unearths the differential effect of financial development on innovation. Specifically, while the banking sector deepening positively enhances patent applications (innovation), improved equity markets and non-banking sector institutions decrease innovation activities. The authors argue that relative to the banking sector, innovation practices are perceived to be risky for players in the non-banking sector to merit investment in innovation. This assertion is, hence, the negative link. This finding is, however, inconsistent with a study by Hsu et al. (2014). The authors examine the cross-country nexus between innovation and financial development and realise that innovation in high-tech industries is spurred by equity markets as opposed to the credit markets. On the back of the inconclusive evidence on the financial development-innovation nexus, Trinugroho et al. (2021) reassessed how financial development explains cross-country differences in innovation in 68 countries. Consistent with Ibrahim and Vo (2021), Trinugroho et al. (2021) establish the level of threshold at which financial development promotes innovation, suggesting that credit and equity markets development spurs innovation up to a certain point above which further financial development discourages innovation. The existence of threshold effects may potentially signal monopolization traits in channelling funds to prospective innovators.

### 2.2.2 Relationship between environmental factors and innovation

Indeed, innovation levels—whether patents or trademarks—have increasingly become a major issue for discussion, particularly in industrialized economies. Recent evidence by Opoku and Aluko (2021) suggests that an increase in industrialization adversely affects the environment quality via emissions. Mensah et al. (2019) studied the relationship between innovations and $CO_2$ emissions in OECD countries and found that eco-patents and trademarks, as the critical components of innovation, dampen $CO_2$ emissions. Khan et al. (2019) found evidence which shows that environmental degradation is reduced by innovation in both the short and long run in Pakistan. This evidence suggests that technologies will improve when innovations in research and development lead to environmental quality. The results of innovations are akin to earlier studies (see, for instance, Jordaan et al., 2017). However, this finding is inconsistent with Murshed (2022), who observes that clean technology innovation adversely affects $CO_2$ emissions, thus heightening environmental degradation. Johnstone et al. (2010) examine the impact of environmental policies on innovation—proxied by patent activity—relying on data from 25 countries spanning 1978–2003. The authors find that R&D spending on renewable-specific endeavors is an important determinant of innovation, particularly for geothermal, wind and solar technologies. Further evidence also suggests that the passage of the Kyoto Protocol in 2005 significantly resulted in the uptake of innovative activities. This evidence is akin to the

study by Liu et al. (2019), who found that promulgating the Kyoto Protocol positively influenced innovation in renewable energy. In the case of China, Ahmad et al. examined the nexus between renewable energy and environmental degradation over the period 1995–2014. Their study reveals that lower consumption of renewable energy exacerbates environmental pollution ($CO_2$ emissions) with a more pronounced long-run effect for Ningxia and Shaanxi.

### *2.2.3 Relationship between environmental factors, financial development and innovation*

Key existing studies (notably Rafindadi & Ozturk, 2016; Majeed & Mazhar, 2019) opine that countries' level of financial sector development is a critical conduit to promoting environmental quality by financing projects that are environmentally compliant. The finding of Godil et al. (2020) shows that improved financial development significantly contributes to spurring economic efficiency by providing a higher opportunity for the adoption of advanced technology. Khan et al. (2021) provide mixed evidence regarding the nexus between financial development and environmental pollution based on different estimation techniques using a sample of 184 countries. The authors find that improved financial development lowers $CO_2$ emissions when estimated using the system GMM. However, when estimated using the seemingly unrelated regression, financial development heightens $CO_2$ emissions. In a related study, Zia et al. (2021) observe that both countries' levels of financial sector development and natural resources exert considerable positive effects on ecological footprint. More specifically, countries rich in national resources and those with improved financial development lead to higher environmental pollution. Indeed, utilization of natural resources through social production and consumption causes environmental pollution (Ding & Peng, 2018).

Regarding the tripartite linkage, Pham (2019), relying on data from 22 OECD countries and the fixed effects Poisson estimation technique, observes that improved financial development significantly enhances innovation. It was further observed that the overall impact of financial development depends on the intensity of carbon dioxide. Focusing on energy, Baloch et al. (2021) investigated the relationship between financial development, innovation and environmental degradation while controlling for the important role of globalisation in OECD countries. The evidence from the study relying on panel data from 1990 to 2017 and the panel Auto Regressive Distributed Lag (ARDL) model suggests that financial development and globalisation significantly promote energy innovation but reduce greenhouse gas emissions. Ibrahim and Vo (2021) investigated innovation-financial development-pollution linkages relying on data spanning 1991–2014 from 27 industrialized countries. Results from their study reveal that innovation only reduced environmental degradation up to a certain threshold level above which further innovation pollutes the environment. On the financial development effect, the authors observed that lower environmental degradation is associated with higher financial development. Again, it was revealed that the impact of environmental quality as a result of financial sector development in countries is dampened by enhanced innovation. In a recent study, Li and Shao (2023) examined the role of financial development and environmental policy stringency in promoting renewable energy innovation in 37 OECD countries using the non-linear panel threshold model. They established a non-linear positive effect between financial market development and renewable energy innovation in mid- and high-level regimes, suggesting that a mature financial market fosters renewable energy innovation. Besides, it was realized that stringent environmental policy enhances renewable innovation.

From the foregoing, it can be seen earlier efforts have been made to analyze the tripartite links between financial development, environmental degradation, and innovation. Nevertheless, most of these studies offer mixed results, necessitating further studies to inform policy. Additionally, extant studies (such as Pham, 2019; Li & Shao, 2023) have analyzed the linkages relying on the narrow measure of $CO_2$ emissions and financial development. There is also the use of dummy variables to denote polluting countries, and the endogeneity issue is yet to be addressed. More importantly, earlier studies have also failed to analyse the conditional effect of financial development in the environment-innovation nexus. Based on these deficiencies in the literature, this present study offers additional insights by analysing the following hypotheses:

***Hypothesis 1(H1):*** The extent of innovation is not only determined by previous levels of financial development but also by the previous levels of environmental degradation, energy consumption and renewable energy.

***Hypothesis 2(H2):*** The effect of environmental factors on innovation is conditional on financial development.

## 3. Methodology

### 3.1 Data

In this study, the data used consists of a balanced panel covering 27 industrialized countries for the 1991–2014 period.[3] This time period and the number of countries were settled due to data availability for all the variables used in the study. Countries with more missing observations for the variables and time period were dropped to ensure we have balanced panel data for analysis. We relied on ecological footprint as our key measure of environmental degradation. This variable measures pollution from six areas such as forest area, fishing grounds, carbon demand on land, cropland, grazing land, and built-up land. As a robustness check, we also use $CO_2$ emissions. Innovation is proxied by the total national spending on research and development as a percentage of GDP. Financial sector development is proxied by an index of financial markets and institutions, which is multidimensional and considers the extent of countries' financial sector access, efficiency, and depth (see Svirydzenka, 2016). This financial development index is normalized to 0 (low) and 1 (high). The remaining variables are energy consumption, renewable energy, real GDP per capita, foreign direct investment (FDI), human capital, and trade openness. The measurement and source for each variable have been shown in Table 1.

### 3.2 Theoretical model specification

Following Furman et al. (2002) and Krammer (2009), we guide our empirical analysis with the national innovation capacity theoretical framework. This framework draws from three main previous research, including ideas-driven endogenous growth theory (Romer, 1990), research on national innovation systems (Nelson, 1993), and the cluster-based theory of national industrial competitive advantage, to allow for wide-ranging country-specific factors to influence innovation. In modelling the national innovation capacity framework, Furman et al. (2002) divided the factors into three categories (such as 'the common pool of institutions, resource commitments, and policies that support innovation; the particular innovation environment in the industrial clusters of countries; and the linkages between them') and relied on the ideas production function of the endogenous growth theory as a baseline model specified as follows:

$$\dot{A}_{jt} = \delta_{jt}(X_{jt}^{INF}, Y_{jt}^{CLUS}, Z_{jt}^{LINK}) H_{jt}^{A\lambda} B_{jt}^{\phi} \quad (1)$$

where $\dot{A}_{jt}$ represents the flow of new-to-the-world technologies, $H_{jt}^{A}$ is the level of resources) devoted to the ideas sector in a country; $B_{jt}$ denotes the overall stock of knowledge held by a country to enhance ideas production in the future; $X_{jt}^{INF}$ is the level of policy choices and resource commitments that constitute the common innovation infrastructure; $Y_{jt}^{CLUS}$ is the particular environment for innovation in a country's industrial clusters; and $Z_{jt}^{LINK}$ represents the strength of the linkages between common infrastructure and industry clusters of a country. In sum, Eq. (1) is the theoretical model for examining

**Table 1.** Measurement of variables and source.

| Variable | Measurement | Source |
|---|---|---|
| INNO | Total domestic R&D expenditure (% of GDP) | OECD |
| FIND | Financial development index (access, depth, and efficiency) | International Monetary Fund- Svirydzenka (2016) |
| EN_DEG | Ecological footprint per capita | Global Footprint Network |
| | $CO_2$ emissions (kg) | World Development Indicators |
| REN_ENER | Share of renewable energy in total energy consumption | World Development Indicators |
| EN_CONS | Energy use (kilogram of oil equivalent per capita) | World Development Indicators |
| FDI | Foreign direct investment, net inflows (% of GDP) | World Development Indicators |
| TRADE | Sum of imports and exports (% of GDP) | World Development Indicators |
| HUCAP | School enrollment, primary (% gross) | World Development Indicators |
| RGDPPC | Gross Domestic Product per capita (constant 2010 US dollars) | World Development Indicators |

the relationship between innovation and observable factors contributing to innovative performance (such as financial development and environmental factors).

### 3.3 Empirical strategy

Our overarching empirical approach is based on the model as follows:

$$\begin{gathered} INNO_{it} = \alpha_o + \alpha_1 INNO_{it-1} + \alpha_2 FIND_{it-1} + \alpha_3 ENVD_{it-1} + \alpha_4 CON_{it-1} + \varepsilon_{it-1} \\ \varepsilon_{it-1} = \delta_i + \sigma_{t-1} + \mu_{it-1} \end{gathered} \tag{2}$$

where $INNO_{it}$ is innovation; $FIND_{it}$ is financial development; $ENVD_{it-1}$ represent different proxies used to capture environmental factors, including environmental degradation (EN_DEG), energy consumption (EN_CONS) and renewable energy (REN_ENER); $CON_{it-1}$ is the control variables including foreign direct investment, trade openness, human capital, and real GDP per capita; $\varepsilon_{it-1}$ is the error term; $\delta_i$ is unobservable country fixed effect; $\sigma_t$ is time effects; $\mu_{it-1}$ is idiosyncratic random term; $i$ is country index while $t$ time index.

We take lag of all our regressors by one period in order to avoid contemporaneous feedback between them and innovation. In addition, we also argue that their impact on innovation is not instantaneous but rather assumes a lag effect as, for instance, the current extent of innovation will depend on, among others, the past year's financial development.

We estimated all our equations using the system Generalized Method of Moments (GMM) because of the endogeneity and reverse causality issues following the inclusion of the lagged terms, which may correlate with $\varepsilon_{it-1}$. (see Abdullah & Tursoy, 2021; Bandyopadhyay & Barua, 2016; Horvey et al., 2023). The system GMM relies on internally determined instruments, and to sidestep the instrument proliferation problem, we collapse the instruments following Roodman's (2009) procedure, which also controls for cross-sectional dependence, which might be present in the panel. Notably, for the internally determined instruments, we used two lags of our explanatory variables as instruments in the first difference equation since all the explanatory variables may be endogenous. Nevertheless, one lag of the first difference of the explanatory variables were used as instruments in the level equation (see Arellano & Bond, 1991; Horvey et al., 2023; Kumi et al., 2017).

The reliability of our findings was examined by assessing the simultaneity issues, identification process, and the assumption of exclusion restriction underlying the identification process. The Difference-in-Hansen Test (DHT) is used to assess the exclusion restrictions. The null hypothesis of this test is that exclusion restriction holds. We also assessed the validity of our instruments by checking for over-identifying restrictions using the Hansen and Sargan tests.

To examine how financial development moderates the link among degradation, energy consumption and renewable energy, we include a term of interaction between financial development and these variables as shown in Eq. (3):

$$INNO_{it} = \gamma_o + \gamma_1 INNO_{it-1} + \gamma_2 FIND_{it-1} + \gamma_3 ENVD_{it-1} + \gamma_4 CON_{it-1} + \gamma_5 (FIND_{it-1} \times ENVD_{it-1}) + \varepsilon_{it-1} \tag{3}$$

where $ENVD_{it}$ is the vector of environmental degradation, energy consumption and renewable energy. It is important to note that the energy variables were used for robustness checks in our analysis.

We evaluate the marginal effects based on Eq. (3) by taking the partial derivative of innovation with respect to environmental factors and this produces Eq. (4) below:

$$\frac{\partial INNO_{it}}{\partial ENVD_{it-1}} = \gamma_3 + \gamma_5 FIND_{it-1} \tag{4}$$

Based on Eq. (4), the following outcomes are deduced:

1. If $\gamma_3 > 0$ and $\gamma_5 > 0$, it means environmental factors increase innovation and financial development magnifies the positive effect of environmental factors on innovation.
2. If $\gamma_3 < 0$ and $\gamma_5 < 0$, it means environmental factors decrease innovation and financial development magnifies the negative effect of environmental factors on innovation.

3. If $\gamma_3 > 0$ and $\gamma_5 < 0$, it means environmental factors increase innovation and financial development reduces the positive effect of environmental factors on innovation.
4. If $\gamma_3 < 0$ and $\gamma_5 > 0$, it means environmental factors decrease innovation and financial development reduces the negative effect of environmental factors on innovation.

The overall marginal effects are estimated at the mean, maximum and minimum values of financial sector development based on the descriptive statistics shown in the next section.

## 4. Findings and discussions

In this section, we present the findings on the tripartite linkages between financial development, environmental degradation, and innovation. The summary statistics of all variables employed in the study are first presented in Table 2.

From the table, the average R&D spending which is our proxy for innovation is 1.57% of GDP while that of financial development is 0.60. This suggests that over the sample period, R&D spending is low even though the countries have well-developed financial sector given that the financial development index is closer to 1.

Beyond these descriptive statistics, we present findings of the system GMM estimations on the tripartite linkages between financial development, environmental degradation, and innovation, as shown in Tables 3 and 4. We begin with the model diagnostics. For all the estimated models, we find evidence that the instruments are valid, and this was based on our failure to reject the null hypotheses of the Sargan and Hansen tests of over-identifying restriction. Similarly, we also failed to reject the null hypotheses of the Difference in Hansen Test for exogeneity of instruments.

In Table 3, consistent with our first hypothesis, a significant positive nexus between financial development and innovation was observed. This suggests that higher financial development increases innovation (column 1).[4] Here, the study finds that a percentage increase in financial development enhances innovation by 0.5329% and this effect is significant at 1% level. This finding is consistent with the extant theory (see Dabla-Norris et al., 2012; King & Levine, 1993; Schumpeter, 1912; Tadesse, 2005) and the strands of empirical evidence claiming that financial development promotes innovation (e.g. Kapidani & Luci, 2019). This is the case when industralised countries improves its financial sector to allocate resources efficiently and also finance technological investments to facilitate innovations (Ibrahim & Alagidede, 2018). As emphasized by Liu et al. (2021), accelerating financial development has the tendency to eliminate financial constraints that prevents investment in technology and consequently enhance innovation.

In columns 2–4, we control environmental degradation using different proxies to examine how they individually affect innovation and determine how sensitive financial development is to the model specification. In column 2, we also observe that, regardless of the measure of environmental degradation, the financial development coefficient still maintains a positive and significant effect. However, the coefficient is lower relative to that of column 1. For instance, when pollution is proxied by ecological footprint, financial development increases innovation by 0.1038% (column 2) following a unit-percentage rise in financial development. However, the same 1% change in financial development spurs innovation by 0.4128% when degradation is measured by $CO_2$ emissions (column 4).

**Table 2.** Summary statistics.

| Variable | Symbol | Mean | Minimum | Maximum |
|---|---|---|---|---|
| Innovation | INNO | 1.568 | 0.177 | 4.077 |
| Financial development | FIND | 0.602 | 0.107 | 1.000 |
| Ecological footprint | EN_DEG | 5.330 | 0.061 | 10.481 |
| Carbon dioxide emissions | EN_DEG | 713,116.6 | 19,926.48 | 1.03e + 07 |
| Renewable energy | REN_ENER | 12.108 | 0.325 | 61.378 |
| Energy consumption | EN_CONS | 3,893.401 | 736.851 | 8,455.547 |
| Foreign direct investment | FDI | 4.565 | −15.838 | 86.589 |
| Trade openness | TRADE | 83.132 | 16.013 | 437.326 |
| Human capital | HUCAP | 102.775 | 79.857 | 124.376 |
| Real GDP per capita | RGDPPC | 32,176.41 | 786.129 | 91,565.73 |

**Table 3.** Financial development, environmental degradation, and innovation nexus.

| | | Ecological footprint | | $CO_2$ emissions | |
|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) |
| Constant | 5.1233 | 0.5449 | 0.3798 | 0.0750 | 1.6878 |
| | (0.000) | (0.432) | (0.716) | (0.954) | (0.279) |
| Lagged INNO | 0.6626*** | 0.4774*** | 0.5113*** | 0.3607*** | 0.3762*** |
| | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) |
| FIND | 0.5329*** | 0.1038** | 0.5998*** | 0.4128*** | 1.7473** |
| | (0.000) | (0.047) | (0.002) | (0.000) | (0.042) |
| TRADE | 0.0001 | 0.0650* | 0.1017* | 0.2543*** | 0.2381*** |
| | (0.997) | (0.076) | (0.087) | (0.000) | (0.000) |
| HUCAP | 1.0401*** | 0.7752*** | 0.4145** | 1.1235*** | 1.3898*** |
| | (0.000) | (0.000) | (0.047) | (0.001) | (0.000) |
| RGDPPC | 0.0077*** | 0.3955*** | 0.3487*** | 0.2168*** | 0.2484*** |
| | (0.000) | (0.000) | (0.002) | (0.000) | (0.000) |
| FDI | 0.0129*** | 0.0164** | 0.0336*** | 0.0187** | 0.0204** |
| | (0.003) | (0.011) | (0.000) | (0.021) | (0.026) |
| EN_DEG | – | –0.3479*** | –0.5159*** | 0.1799*** | 0.1247*** |
| | | (0.000) | (0.002) | (0.000) | (0.008) |
| Interactions | | | | | |
| FIND × EN_DEG | | – | 0.4812*** | – | 0.1164* |
| | | | (0.003) | | (0.063) |
| Diagnostics | | | | | |
| Second-order serial correlation | 0.346 | 0.188 | 0.371 | 0.172 | 0.105 |
| Sargan test (*p*-value) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Hansen test(p-value) | 0.639 | 0.450 | 0.364 | 0.640 | 0.483 |
| DHT instruments test: | 0.450 | 0.312 | 0.169 | 0.320 | 0.205 |
| GMM instruments (levels): | | | | | |
| Hansen test excluding group | | | | | |
| Difference (null H = exogenous) | 0.730 | 0.604 | 0.723 | 0.896 | 0.843 |
| Instruments | 10 | 10 | 10 | 10 | 10 |
| Fisher test (*p*–value) | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Values in parentheses are the *p*-values. INNO = Innovation; FIND = Financial development; HUCAP = Human capital; RGDPPC = Real GDP per capita; FDI = Foreign direct investment; EN_DEG = Environmental degradation; TRADE = Trade openness.

With regard to the effects of environmental degradation, we find that while ecological footprint reduces innovation, $CO_2$ emission is associated with higher innovation. From column 2, innovation reduces by 0.3479% following a 1% increase in ecological footprint compared to a 0.1799% increase in innovation when $CO_2$ emission rises by 1%. Given the size of the coefficients, we observe that the impact of ecological footprint on innovation is consistently higher relative to that of $CO_2$ emission. This is so because the ecological footprint comprises a wider multitude of anthropogenic factors, including $CO_2$ emissions. The differences in the direction of effects of ecological footprint and $CO_2$ emissions suggest that the impact of environmental degradation on innovation is conditioned on the measure of degradation, with the dampening impact of ecological footprint steadily higher compared to $CO_2$ emissions. The evidence of environmental degradation (proxied by ecological footprint) reducing innovation aligns with the study of Wang et al. (2022). The authors found that 'firms located in cities with an exogenous source of heavy pollution tend to adopt less green innovation.' By contrast, the positive outcome of $CO_2$ emissions on innovation is supported by the Porter hypothesis and the extant study of De Vries and Withagen (2005), which shows that higher emissions trigger strict environmental policy encouraging more innovation. Overall, the implication of our finding here suggests that increasing pollution levels in industrialised countries could lead to concerns about environmental sustainability. Such concerns can trigger the formulation and adoption of innovative technologies to reduce pollution. This evidence holds for $CO_2$ emissions and not for ecological footprint.

Given this understanding, how does financial development moderate the impact of environmental pollution on innovation? We provide answers to this research question by examining the multiplicative interaction term of financial development and environmental degradation to achieve the second research objective. The addition of the interactive term of financial development and environmental pollution allows us to find out whether improved financial development dampens or magnifies the impact of environmental degradation on innovation, as shown in Eq. (3). In other words, we examine how financial development moderates the relationship between environmental degradation and innovation. Our hypothesis here is that financial systems in highly innovative countries are able to exert counteractive

**Table 4.** Financial development, energy consumption, renewable energy, and innovation.

| | Energy consumption | | Renewable energy | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| Constant | 5.0318 | 5.3023 | 6.3475 | 7.0370 |
| | (0.000) | (0.002) | (0.000) | (0.000) |
| Lagged INNO | 0.7037*** | 0.5515*** | 0.5562*** | 0.5598*** |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| FIND | 0.4854*** | 0.5304*** | 0.5474*** | 0.5859*** |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| TRADE | 0.0236 | 0.0418 | 0.0538* | 0.0280 |
| | (0.346) | (0.188) | (0.055) | (0.528) |
| HUCAP | 0.9562*** | 0.9325*** | 1.2461*** | 1.3616*** |
| | (0.000) | (0.003) | (0.000) | (0.000) |
| RGDPPC | 0.0120*** | 0.0581*** | 0.0152*** | 0.0079*** |
| | (0.000) | (0.000) | (0.000) | (0.000) |
| FDI | 0.0036 | 0.0040 | 0.0228*** | 0.0202** |
| | (0.168) | (0.365) | (0.000) | (0.044) |
| EN_CONS | 0.0629*** | 0.1016*** | – | – |
| | (0.008) | (0.004) | | |
| REN_ENER | – | – | 0.0092*** | 0.0091** |
| | | | (0.006) | (0.032) |
| Interactions | | | | |
| FIND × EN_CONS | – | 0.0001* | – | – |
| | | (0.059) | | |
| FIND × REN_ENER | – | – | – | 0.0026 |
| | | | | (0.972) |
| Diagnostics | | | | |
| Second-order serial correlation | 0.438 | 0.268 | 0.378 | 0.399 |
| Sargan test (*p*-value) | 0.000 | 0.000 | 0.000 | 0.000 |
| Hansen test (*p*-value) | 0.870 | 0.929 | 0.496 | 0.461 |
| DHT instruments test: | 0.299 | 0.397 | 0.326 | 0.201 |
| GMM instruments (levels): | | | | |
| Hansen test excluding group | | | | |
| Difference (null H = exogenous) | 0.956 | 0.866 | 0.661 | 0.818 |
| Instruments | 10 | 10 | 10 | 10 |
| Fisher test (*p*–value) | 0.000 | 0.000 | 0.000 | 0.000 |

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Values in parentheses are the *p*-values. INNO = Innovation; FIND = Financial development; HUCAP = Human capital; RGDPPC = Real GDP per capita; FDI = Foreign direct investment; EN_DEG = Environmental degradation; TRADE = Trade openness; EN_CONS = Energy consumption; REN_ENER = Renewable energy.

effects on environmental degradation, and this, together, plays an important role in influencing the speed of innovation. In this endeavour, we introduce the interactive term of environmental degradation and financial development into the innovation equation, as shown in columns 3 and 5. We find that while the coefficients of $CO_2$ emissions and ecological footprint are respectively positive and negative, the interactive term has a significant positive coefficient. Thus, while the ecological footprint lowers innovation, higher financial development dampens its negative effect on innovation. Our second hypothesis is upheld here. Similarly, well-developed financial markets magnify the innovation-enhancing effect of $CO_2$ emissions. The marginal effects of financial development based on Eq. (3) is evaluated, and the results are presented in columns 3 and 5. When evaluated at the minimum level of ecological footprint, financial sector development has a marginal effect of 2.027% and increases to 4.563 and 7.041% at the mean and maximum levels of ecological footprint, respectively. This dynamic is also observed for $CO_2$ emissions. Hence, the impact of the financial sector is strengthened once we include its role in the environmental degradation-innovation nexus. This finding is consistent with Pham (2019) and Aristizabal-Ramirez et al. (2017).

Turning to the control variables, the study finds that all the control variables positively and robustly affect innovation except for trade openness, which is not significant in the first estimation (column 1). Human capital enhances innovation, where a percentage increase in human capital significantly spurs innovation by 1.04%. This effect reduces to 0.775% when the ecological footprint is controlled for (column 2). However, the impact of human capital stock increases to 1.125% when environmental degradation is proxied by $CO_2$ emissions (column 4). In columns 3 and 5, where we include the interactive term, the impact of human capital remains positive, with the highest magnitude registered when environmental degradation is measured by $CO_2$ emissions (column 5). The evidence on human capital innovation is intuitively appealing and consistent as increased education and accumulation encourage

innovation (Ibrahim, 2018). This is the case since highly educated individuals will demonstrate knowledge and the capacity to foster innovation. A key implication is that an educated workforce supports deepening innovation, which is consistent with the findings of the extant studies (e.g. Oluwatobi et al., 2016; Osei, 2023).

Real GDP per capita is also positively and robustly related to innovation, where a unit-percentage increase in per capita income spurs innovation by 0.0077% (column 1) with this impact increasing to at most 0.3955% (column 2). The absolute effect of real GDP per capita is greater when environmental degradation is proxied by ecological footprint relative (columns 2 and 3) to $CO_2$ emissions (columns 3 and 5). Innovation is higher in countries with higher economic development since innovation entails spending on R&D. Conversely, economies with lower income per capita are less likely to spend more on innovation since investment in technology which are often income and capital-intensive. Our finding is similar to Furman et al. (2002) and Hu and Mathews (2005), who found GDP per capita to be positively related to innovation output.

Similarly, sustained inflow of FDI is also associated with higher innovation, with the coefficients ranging between 0.0129 and 0.0336. Notice that the innovation-enhancing impact of FDI is higher in the estimations with the multiplicative interactive terms of financial development and pollution (columns 3 and 4). The FDI-innovation link suggests that the attraction of foreign investors spurs innovation. One reasonable explanation is that foreign direct investment inflows potentially serve as a source of cheaper financial capital, which can allocated to innovation-related endeavour (Osei, 2023). To the extent that FDI is also associated with technology spillover into the host country, such a positive and robust impact of FDI is expected (Ibrahim & Acquah, 2021; Rafindadi et al., 2018).

### *4.1 Robustness analysis*

We conduct robustness analysis by controlling for renewable energy and energy consumption and their interactions with financial development. In other words, we examine the effect of renewable energy, energy consumption, and how financial development moderates their relationships with innovation. Table 4 presents the results.

From the table, it is vivid that all the findings are consistent with the baseline results in Table 3. Specifically, financial development robustly enhances innovation in all the regressions, confirming our earlier findings that improved financial sector development is associated with higher innovation. In columns 1–2, where we control energy consumption, innovation significantly rises by 0.4854 and 0.5302% when there is a 1% percentage increase in financial development. Similarly, the coefficients of financial development increase to 0.5474 and 0.5859 when renewable energy and its interaction with financial development are included in the specifications (columns 3 and 4). In column 1, we observe that energy consumption spurs innovation with a coefficient of 0.0629, which is statistically significant at all conventional levels. Similarly, renewable energy heightens innovation, where a 1% rise in renewable energy heightens innovation by 0.0092% (column 3). Thus, while both energy consumption and the extent of renewable energy support innovation, the effect of energy consumption is exceedingly higher. After investigating the moderating effects of financial development using the interactive term, we found a positive coefficient for the interactive term. This suggests that while both renewable energy and energy consumption exert positive effects on innovation, improved financial markets magnify their positive effects. However, the ability of financial systems to spur the innovation-enhancing effect is only marginally significant for energy consumption (column 2) with no apparent effect on renewable energy. An assessment of the marginal effects of financial development conditions on the levels of energy consumption yields 0.6041% at the minimum, which increases to 0.9197 and 1.3760% at the mean and maximum levels, respectively.

Therefore, our evidence shows that financial development has a far more substantial effect on innovation, especially in countries with high environmental degradation and energy consumption. Anecdotally, countries with high levels of pollution and energy intensity may have made significant strides in lowering their pollution levels and energy consumption by boosting investment in technologies that reduce pollution, with the financial sector providing the needed financial resources.

## 5. Conclusion

This study examined the relationship between financial development and innovation in addition to investigating how financial markets interact with environmental degradation, energy consumption, and renewable energy to influence innovation in some selected industrialized countries. The study uncovered the three important findings by invoking the generalized method of moments (two-step) on a panel data comprising 27 countries over the period 1991–2014. First, higher financial development robustly increases innovation. Second, while higher energy consumption, renewable energy and $CO_2$ emissions spur innovation, increases in ecological footprint lowers innovations. Third, an improved financial sector reduces the negative impact of ecological footprint on innovation while propelling the innovation-enhancing impact of energy consumption and $CO_2$ emissions with no apparent effect on renewable energy. Thus, financial development has a far more momentous effect on innovation in countries with high environmental degradation and energy consumption. This dynamic is because heavily polluted countries and those with high energy intensity may be much concerned with the extent of their degradation. Hence, identifying more innovative ways to lower pollution by boosting the investment in environmentally friendly technologies with the financial sector supporting the right financial resources. A key recommendation of the study is that countries should pursue policies that develop the financial sector. This is because improved financial sectors do not only directly inspire industries to innovate but also indirectly dampen the negative effects of pollution on innovation. Specifically, governments in industralised countries can make a substantial effort to develop further the financial market related to renewable energy to minimize financial risk and ensures greater returns. The development of the carbon finance market is necessary to trigger technological innovation. There is also the need for financial development strategies to consider granting bank credit to support innovation to environmentally friendly enterprises. In addition, macroeconomic management should be strengthened to improve factors such as human capital, foreign direct investment, trade openness and real GDP per capita to complement the strategies of further developing the financial sector in industralised countries to promote innovation. While this study makes important contributions to the literature, it is limited in data availability for all countries in industralised countries and the time period. Future studies can improve on this and examine the threshold effect of energy efficiency and governance in the financial development-innovation relationship.

## Notes

1. Out of the 132 countries ranked, the first countries are all members of industrialized countries.
2. As a robustness check, the $CO_2$ emissions variable was employed.
3. The 27 countries selected for the study include Australia, Belgium, Canada, China, Denmark, Finland, France, Germany, Hungary, Ireland, Italy, Japan, Korea, Mexico, Netherlands, Norway, Poland, Portugal, Romania, Russia, Singapore, Slovak Republic, Spain, Switzerland, Turkey, United Kingdom, and the United States.
4. We rely on the first lags of all the explanatory variables. However, the results are also robust even considering their second lags.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

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## Data availability statement

Data available on request from the authors.

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