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## Article

Examining the dynamics between banking sector performance, environmental sustainability, and environmental technology innovation: evidence from G20 countries

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# Examining the dynamics between banking sector performance, environmental sustainability, and environmental technology innovation: evidence from G20 countries

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## ABSTRACT

Previous studies examined sustainability-innovation and banking-innovation linkages separately. This research addresses that gap by jointly analyzing the relationships between environmental sustainability, five banking performance metrics, and technology innovation in G20 nations from 1990 to 2022. The study constructs a banking performance index from five indicators, including return on assets, equity, deposits as a percent of GDP, risk scores, and market capitalization. A comprehensive IV-GMM approach controls for endogeneity using lagged variables as instruments in a two-step GMM model, along with the Lewbel method. Additional robustness is provided by cross-sectional, time-series FGLS regression. Results show sustainability consistently boosts innovation directly. However, examining individual banking metrics reveals that the performance index negatively correlates with innovation, excluding risk scores. Most interaction terms mirror sustainability's influence, though returns and concentrations diverge. Introducing interaction terms also inverts prior index relationships at times. Analyzing direct, interactive, and net impacts offers different views than indexing alone. The performance index positively links to net analyses versus other specifications. Overall, the findings provide empirically grounded insights into these dynamics within influential nations. Non-linearities are observed between aggregate and disaggregate banking indicators. Considering metrics from diverse analytical angles through a multidimensional lens informs optimized policy balances.

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## 1. Introduction

Considering the significant influence of major economies' policies on global sustainability, it is important to explore the relationship between banking sector performance, environmental regulations, and green innovation within G20 nations. The G20's significant global economic influence and population size present great potential for maximizing the benefits of effective collaboration. Although previous studies have provided valuable insights, there are still some gaps that the current research aims to address. Striking a balance between environmental sustainability and economic growth is a persistent global challenge, as highlighted by the Intergovernmental Panel on Climate Change (Bannerman, 2020; Guang-Wen et al., 2023). All sectors must make efforts to achieve the ambitious global goals related to addressing climate change. The banking sector plays a vital role in directing capital towards various business activities (Shahab et al., 2018). Simultaneously, advancements in environmental technology are driving the development of solutions that can effectively decarbonize economies and mitigate various impacts (Hsu et al., 2021).

Recent research has examined multiple factors that impact environmental sustainability and innovation. Studies have demonstrated that governance mechanisms such as board diversity (Elmagrhi et al., 2019) and sustainability committees (Tran et al., 2021) have a positive influence on disclosure and performance. However, it has been found that stricter regulations do not enhance the role of boards in

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promoting disclosure (Tran et al., 2021). Peer effects can also serve as a motivation for innovation, as firms tend to imitate perceived leaders in the field (Machokoto et al., 2021). Initiatives that are associated with markets do not always lead to desired outcomes and instead may contribute to the perception of 'greenwashing,' as described by Haque and Ntim (2022) and Orazalin et al. (2024). Sharing credit information has been found to decrease loan defaults, but this effect is dependent on the level of concentration, as shown in a study by Fosu et al. (2020). Nevertheless, the quality of governance had a minimal effect on mitigating these impacts. Sustainability is influenced by policies, leadership, peers, and disclosure, as indicated by Elmagrhi et al. (2019) and Shahab et al. (2020). However, symbolic actions occasionally deviate from bringing about substantial change, as noted by Haque and Ntim (2022) and Orazalin et al. (2024). Considering the significant influence of major economies' policies on global sustainability, it is necessary to investigate the relationship between the performance of the banking sector, environmental regulations, and green innovation in G20 nations. The G20, which represents more than 85% of global GDP and two-thirds of the world's population (Wang & Dong, 2021) has the potential to generate significant advantages by maximizing cooperation and collaboration between these domains. Although previous studies have provided valuable insights, there are still certain gaps that the current research aims to fill. The simultaneous pursuit of environmental sustainability and economic growth poses a persistent challenge for nations globally (Haque & Ntim, 2018). Comprehensive measures are required in all industries to achieve ambitious global objectives related to climate change mitigation. The banking sector plays a crucial role in directing capital towards business. Simultaneously, the advancement of environmental technology fosters solutions that can facilitate the reduction of carbon emissions in economies and mitigate various environmental consequences (Hsu et al., 2021).

Research has established connections between financial development, sustainability, and innovation on a global scale (Hsu et al., 2021; Liu et al., 2021). Technological advancements contribute to the reduction of emissions and support sustainable economic growth (Abid et al., 2022). Various quantitative methods, such as data envelope analysis (DEA), regression, and panel analysis, have been used to evaluate the relationships between variables (Anser et al., 2020; Khattak et al., 2020; Liu et al., 2021). These studies suggest the presence of nonlinear effects in the environmental Kuznets curve. Prior analyses have examined the connections between financial development, sustainability metrics, and green innovations. Multiple studies (Cao et al., 2021; Lv et al., 2021; Umar & Safi, 2023) have identified that the implementation of policies that promote renewable energy, environmentally-friendly technologies, and robust institutions has a consistent and positive impact on reducing emissions and improving sustainability over a period of time. Digital finance plays an active role in driving innovation in green technology, especially in areas where traditional finance falls short. Various factors, such as the implementation of renewable energy, advancements in green technology, and the quality of policies and regulations, can have a non-linear impact on outcomes, which is dependent on the initial conditions (Anu et al., 2023; Y. Sun et al., 2022).

Prior research has primarily focused on assessing the influence of factors like sustainability and financial development on technological progress alone (Hsu et al., 2021). However, this approach overlooks the potential feedback effects of innovation on sustainability outcomes, resulting in an incomplete understanding. Despite the close interconnection of financial, policy, and research and development (R&D) domains in reality, previous studies have not extensively examined the potential benefits of effectively aligning economic, regulatory, and innovation strategies (Lv et al., 2021). Furthermore, the practice of examining individual elements separately is more common than conducting integrated analyses that unravel the interactions between banking, regulations, and cutting-edge solutions (Liu et al., 2021). A limited concentration hinders the exploration of how optimizing the harmony between these domains could result in significant environmental advantages, given that major nations have a disproportionate influence on global affairs. Conducting focused studies on connections within influential G20 settings could help address these empirical limitations and provide a deeper understanding.

While some information is available, extensive research specifically focusing on these dynamics within the influential G20 group of countries remains lacking. This study aims to fill this gap by examining the correlations between the performance of the banking sector, measures of environmental sustainability, and the innovation of environmental technology in G20 countries. This study will examine how variables such as investments in renewable energy and green innovations affect emission levels and patterns of resource consumption. The purpose of insights is to provide information

for G20 nations that are looking to promote economic development and environmental stewardship through their policies. The objective of this study is to gain new insights into the relationship between banking, sustainability, and innovation. It focuses on examining the technological impact of sustainability and the potential influences of banking. Many G20 nations are setting long-term development goals, but achieving environmentally sustainable growth is challenging and requires further investigation in different economic contexts (Alam et al., 2022; W. Cai & Li, 2018; Lu & Chesbrough, 2022). Efficiency and environmentally friendly manufacturing have improved in G20 countries. However, there are still obstacles that hinder economically sustainable progress. A deeper understanding of global production and consumption challenges is necessary to overcome these obstacles.

Furthermore, it is crucial to analyze the connections between finance, technology, and environmental performance among G20 nations at a regional level. However, our understanding of the relationship between these factors remains incomplete (Cao et al., 2021; Kurniawan et al., 2023). This research, driven by a desire to address knowledge gaps, diligently examines the key factors involved in evaluating the influence of sustainability on technological advancement and explores the potential role of banking in this context (Jiakui et al., 2023). According to Ozturk et al. (2023), achieving long-term prosperity heavily depends on the extensive implementation of environmentally conscious innovation and resilient growth. Within the G20, there are opportunities to develop cost-effective green industries and transportation by reducing sustainability costs.

Moreover, promoting environmental economic growth requires strong strategies that support the advancement of eco-technology in G20 countries (X. Sun et al., 2023). Implementing effective regulations is a strategy for achieving goals related to clean energy and sustainable finance. This approach promotes progress towards environmentally conscious prosperity by enforcing strong policies and penalties (Abbas et al., 2023; Hasan & Du, 2023; Saeed Meo & Karim, 2022; Yi, 2023). By meticulously analyzing the key themes related to research questions, my objective is to offer comprehensive insights that address the existing gaps among G20 countries.

Several previous studies offer pertinent context for analyzing the interplay between banking, sustainability, and innovation in G20 nations. However, significant research areas remain unexplored. Liu et al. (2021) and Y. Sun et al. (2022) conducted cross-country analyses that provided broad insights but did not specifically focus on the significant G20 bloc. Raza et al. (2023) and Ozturk et al. (2023) used panel methods to assess the factors that influenced sustainability measures in G20 countries between 1990 and 2020. Although both analyses provided information, neither of them included an examination of the banking sector component. The goal of this present study is to build on previous research by focusing solely on the G20 group. Because they are the world's major economies, the G20 members have a significant impact on global target achievement. Therefore, insights focused on the G20 are particularly valuable. However, we have not fully elucidated the complex connections between financial performance, environmental endeavors, and technological solutions in this crucial group. This study aims to address various significant knowledge gaps by examining the interplay between banking, sustainability, and innovation within the G20 framework. Specifically, no previous study has conducted a combined analysis of financial support provision, environmental regulations and impacts, and innovation responses for G20 countries.

By clarifying these connections, G20 governments can develop comprehensive policy frameworks that promote both economic growth and environmental stewardship. The primary contribution is to provide novel insights that can expedite the achievement of internationally agreed sustainability goals within the influential G20 consortium. Attaining sustainable expansion and fostering eco-friendly advancements are becoming increasingly crucial on a global scale. However, we have not thoroughly investigated the precise mechanisms by which sustainability influences technological progress, nor the influence of contextual factors like banking activity on this relationship. This research was motivated by the need to address these knowledge gaps. The study aims to achieve four research objectives:

1. Assess the impact of the banking industry's performance on the development of environmental technology innovation in G20 countries.
2. Evaluate the influence of environmental sustainability on the development of technological advancements.
3. Evaluate the influence of the banking industry's performance with the interaction of environmental sustainability on environmental technology innovation in G20 countries.
4. Analyze the overall net impact of sustainability initiatives on innovation, taking into consideration the influence of financial bank performance.

This research seeks to enhance comprehension of these dynamics within a significant G20 context by empirically examining hypotheses aligned with the objectives. The goal of this study is to provide valuable insights into the connections between the banking sector's performance, environmental sustainability, and environmental technology innovation. While previous studies have separately examined these subjects, a more comprehensive analysis is necessary to comprehend their intricate interactions and bridge the existing knowledge gaps. This study aims to evaluate the overall impact of environmental sustainability on the advancement of eco-friendly technology. Additionally, it aims to explore the potential impact of banking performance on the connection between sustainability and innovation. By addressing these objectives, we anticipate gaining new empirical knowledge about the influence of sustainability on technological development as well as how contextual factors such as banks may influence this relationship. We will utilize the ecological footprint indicator as a comprehensive gauge of environmental performance, ensuring a thorough examination. Moreover, patents pertaining to renewable energy serve as a representative measure of green innovation. The study aims to first use IV-GMM regression to analyze linkages using the most recent G20 data from 1990 to 2022. This will allow for the investigation of dynamics among these elements over time within the major emitter nations. By closely analyzing well-defined relationships that revolve around the research questions, we anticipate gaining valuable new insights that will advance sustainable development goals. The study is structured into seven sections, commencing with an introduction that offers an overview. Then background information, and a review of theoretical literature, a review of empirical literature, a research design, empirical findings, and a conclusion.

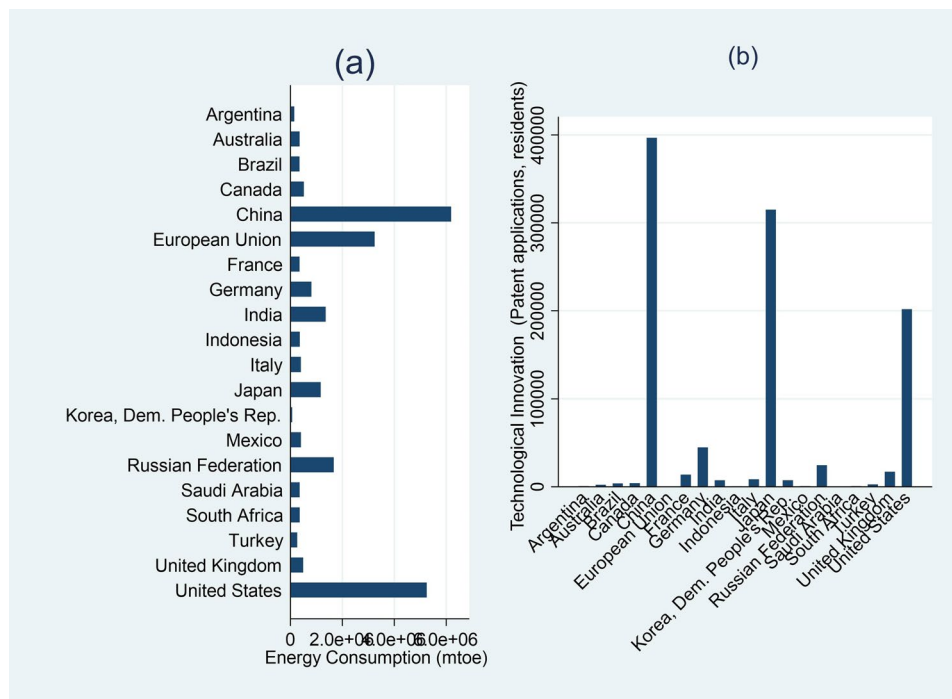
## 2. Background of study

The banking sector's significance in fostering both economic and ecological welfare cannot be understated (Y. Zhang & Zhou, 2020). Governments increasingly rely on the financial system, especially banking institutions, to develop and implement sustainability regulations aimed at issues like climate change (Orazalin et al., 2024). However, relatively little research has examined how expansion of the banking sector may influence levels of environmental innovation and technological progress, despite acknowledgments of banking's important contributions to economic growth (Jiakui et al., 2023). As the focus of this study, the G20 bloc accounts for approximately 84% of global economic output (Bannerman, 2020; D'Orazio & Dirks, 2022), making it highly influential. Unsurprisingly, this means G20 nations also represent a considerable portion of worldwide energy consumption and emissions impacts. As shown in Figure 1, China leads G20 energy consumption at an estimated 260 million tons of oil equivalent, followed by the European Union and the United States. This underscores the importance of examining policies within these major demand-side economies. Figure 1, panel b illustrates technology innovation trends as proxied by patent approvals (Lv et al., 2021), displaying China atop G20 nations for eco-innovations, followed by Japan and the United States based on World Intellectual Property Organization statistics from 2000–2020 (Ozturk et al., 2023). Together, these graphics set the scope of analysis toward the consequential G20 bloc as key leaders in contemporary energy usage (Khattak et al., 2020) and potentially drivers of the solutions needed for transitioning to sustainability goals (Cao et al., 2021; Raza et al., 2023).

Growing emphasis exists on strengthening sustainability rules and guidelines within the banking industry as well. New policies aim to promote green growth, renewable energy deployment, and energy efficiency. Effectively carrying out such initiatives crucially involves harnessing support from the finance sector, with commercial banks playing a primary role in efforts to achieve sustainability targets. The intersection between financial systems and innovation has emerged as a facilitator for tackling various environmental challenges through widespread adoption of eco-friendly technologies and renewable resources (Fan et al., 2022). Previous studies provide evidence that well-performing banking sectors can stimulate renewable energy innovation and sustainable development, as seen in China (Li et al., 2023; Y. Zhang & Zhou, 2020). Access to bank resources and support has been shown to significantly contribute to advancing levels of green innovation over time (Chen et al., 2022).

Recent analyses also find that banks assisting green initiatives and projects tend to demonstrate strong financial performance themselves (Abbas et al., 2023; Alsagr, 2023). The resources provided through commercial and investment banking activities can substantially impact the implementation of green technologies across different industries (Z. Ahmed et al., 2022; Hunjra et al., 2023). Furthermore,





**Figure 1.** (a) Energy consumption in (mt) and (b) technology innovation (patent applicants) of G20 countries.

banking sector performance outcomes seem to correlate closely with enhanced facilitation of wider sustainability efforts. The availability of green venture capital is also dependent on the prosperity of local banking systems (Jiakui et al., 2023; H. Khan et al., 2022). Economic downturns make obtaining financial support more difficult as well (P. Zhang et al., 2023).

This study aims to help address gaps in understanding these linkages by comprehensively evaluating the technological effects of sustainability efforts as well as exploring banking sectors' potential to influence innovation trajectories using data from G20 nations. This will allow for analyses across countries with diverse economic backgrounds, circumstances, and policy environments. Previous work by Yi (2023) examined the interactions between banking performance, environmental sustainability, and eco-technology innovation within the single-country setting of China. Yi acknowledged the importance of these interrelated factors, but he focused on a largely descriptive analysis within national boundaries. The present study aims to build upon this understanding by taking a more comprehensive exploratory approach and investigating the underlying mechanisms and dynamics between these variables across multiple economies. Specifically, this research evaluates these relationships within the diverse and influential group of G20 nations. By examining the broader multi-country context and relationships between intricate factors over time, this study pursues a more sophisticated comprehension of sustainability's technological impacts beyond the scope of single-nation studies. Expanding analysis to an international scale allows for comparison across different economic backgrounds, circumstances, and policy environments within major globally influential settings.

### 3. Theoretical literature review

#### 3.1. Contingency theory as an overarching theoretical framework

Contingency theory provides a valuable theoretical framework for understanding the dynamics between banking sector performance, environmental sustainability, and environmental technology innovation in the context of G20 nations. This theory suggests that the effectiveness of organizational practices and strategies depends on how well they align with the external environment and internal capabilities of the organization (Lee et al., 2016; Lu & Chesbrough, 2022). By drawing on both classic and recent studies,

we can establish a solid theoretical foundation that links the dependent and independent variables together, allowing us to formulate relevant predictions and hypotheses.

### ***3.2. Banking sector performance and environmental sustainability***

The first aspect of our theoretical framework focuses on the relationship between banking sector performance and environmental sustainability. Hsu et al. (2021) emphasize the significance of sustainable business performance in the technology industry and highlight the positive impact of eco-innovation practices on economic, social, and environmental performance. This finding suggests that investments in environmental sustainability can lead to improved overall performance. Moreover, Dai (2023) demonstrate that corporate social responsibility (CSR) and green finance positively influence environmental performance. Hence, we hypothesize that a positive association exists between banking sector performance and environmental sustainability, with banks prioritizing environmental sustainability and showing enhanced overall performance.

### ***3.3. Environmental technology innovation and environmental sustainability***

The second part of our theoretical framework explores the relationship between environmental technology innovation and environmental sustainability. The study by Zakari et al. (2023) underscores the role of eco-innovation strategies, such as eco-process, eco-product, and eco-organizational innovation, in enhancing sustainable business performance. This suggests that technology-driven innovations promoting environmental sustainability can contribute to improved performance outcomes. Furthermore, Dai (2023) find that green innovation mediates the relationship between corporate social responsibility and environmental performance. Based on these findings, we propose a positive association between environmental technology innovation and environmental sustainability, with banks engaging in eco-innovative practices demonstrating a higher level of sustainability (Choubey & Sharma, 2022).

### ***3.4. Linking the variables: the contingent role of market turbulence***

Expanding on contingency theory, we present the role of market turbulence as a moderating factor in the connection between banking sector performance, environmental sustainability, and environmental technology innovation. According to Lv et al. (2021), market turbulence has the potential to enhance the beneficial impact of eco-organizational innovation on social performance. Therefore, the effect of environmental sustainability initiatives and technological innovation on the performance of the banking sector may differ based on the degree of market turbulence. Thus, we propose that market turbulence influences the connections between the performance of the banking sector and environmental sustainability, as well as between environmental technology innovation and environmental sustainability.

Our theoretical framework, based on contingency theory, suggests that there is a relationship between banking sector performance, environmental sustainability, and environmental technology innovation. The framework draws on seminal research such as (Choubey & Sharma, 2022) and Lee et al. (2016) to emphasize the dependent and variable nature of these connections. By integrating recent research, specifically Dai (2023), we improve our comprehension of the favorable connections between banking sector performance, environmental sustainability, and environmental technology innovation. In addition, the researcher introduces market turbulence as a moderating factor, taking into account the contextual influences that may influence these relationships in the Chinese banking sector.

### ***3.5. Theoretical framework***

This study seeks to thoroughly investigate the impact of banking sector performance on the development of environmental technology innovation and sustainability (Al-Ahdal et al., 2023; Hunjra et al., 2023). This research employs the widely used Stochastic Impacts by Regression on Population, Affluence,



and Technology (STIRPAT) theoretical model to conduct the empirical analysis (Dietz & Rosa, 1997; York et al., 2003). Below is the presentation of IPAT Equation (1).

$$I = P * A * T \quad (1)$$

where I represents the impact of the environment, P is the population number, A the affluence, and T the level of technical advancement. Originally developed as an important extension of the basic IPAT identity (Holdren & Ehrlich, 1974), the STIRPAT framework allows investigation of multiple determinants' effects in a multiplicative form (Dietz & Rosa, 1997) and shows using Equation (2) below:

$$C P_{it}^{\alpha_1} A_{it}^{\alpha_2} T_{it}^{\alpha_3} \varepsilon_{it} \quad (2)$$

where  $I_{it}$  represents the environmental impact or outcome of interest for country in time period t. The independent variables include population (P), affluence or wealth (A), and technology (T). The error term is denoted by  $\varepsilon$ , while C represents a constant and the coefficients for each predictor by  $\alpha_1$ ,  $\alpha_2$ , and  $\alpha_3$  respectively. The subscripts indicate the year and country designation. This analysis focuses specifically on environmental impacts quantified as carbon dioxide emissions levels. Potential driver variables include GDP per capita as a measure of affluence, total population size, rates of innovation as captured by patent approvals, and indicators of banking sector performance such as total assets or loans extended. The following sections aim to empirically test relationships between these factors utilizing panel data techniques applied to the G20 sample over recent decades. Banking performance proxies of index (BP) represent 'affluence' (Ch'ng et al., 2021; Creel et al., 2015; Le et al., 2019; Liu et al., 2021). Total patent counts symbolize environmental technologies as the 'impact' (Jiakui et al., 2023; Urbaniec et al., 2021).

#### 4. Empirical literature review and hypothesis development

Considering the significant influence of major economies' policies on global sustainability, it is necessary to conduct a more thorough analysis of the relationship between the performance of the banking sector, environmental regulations, and green innovation in G20 countries. Although previous studies have provided valuable insights, there are still certain gaps that the current research aims to fill.

Prior research has primarily focused on assessing the influence of factors like sustainability and financial development on technological progress alone (Hsu et al., 2021; Liu et al., 2021). However, this approach overlooks the potential feedback impacts of innovation on sustainability outcomes, resulting in an incomplete understanding of the subject. Previous studies have not thoroughly examined the potential benefits of effectively aligning economic, regulatory, and innovation strategies (Cao et al., 2021; Lv et al., 2021) despite the fact that the financial, policy, and research and development sectors are closely interconnected in reality. Furthermore, the practice of conducting separate examinations of individual elements is more common than conducting integrated analyses that unravel the interactions between banking, regulations, and cutting-edge solutions (Hsu et al., 2021; Khan et al., 2022). A limited concentration hinders the exploration of how maximizing harmony between these domains could result in significant environmental advantages, considering that major nations have a disproportionate influence on global matters. Conducting focused studies on connections within influential G20 settings could help improve our understanding by addressing these empirical limitations.

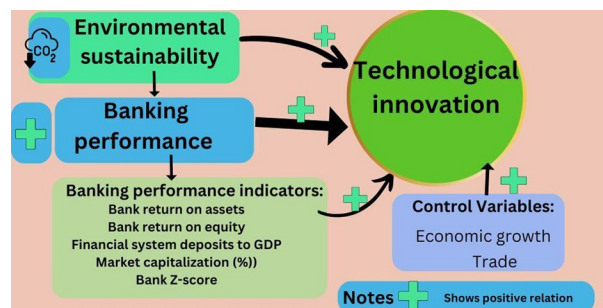
Researchers have thoroughly examined the connections between finance, sustainability, and innovation, suggesting that focused strategies could result in significant returns. Recent evidence suggests that implementing green technologies and allocating funds based on careful selection can effectively reduce emissions at both local and global levels. China, undergoing rapid industrialization, has observed this (Anser et al., 2020; Abid et al., 2022; Hsu et al., 2021; Khan et al., 2022; Khattak et al., 2020). In addition, innovation has a transformative impact by stimulating improvements in efficiency, advancements in clean production, and reductions in carbon emissions that are crucial for both environmental and economic advancement (Abid et al., 2022; Khan et al., 2022). According to certain analysts (Khan et al., 2022), robust socio-political structures also help create favorable conditions for achieving sustainability goals.

The researchers have utilized various quantitative techniques such as data envelope analysis (DEA), regressions, and panel data analysis to account for cross-sectional and temporal data interdependencies. This approach has enhanced the validity and generalizability of their findings (Anser et al., 2020; Khan et al., 2022; Khattak et al., 2020). Khan and his co-authors discovered evidence of a groundbreaking ‘tipping point’ in emissions that is linked to the levels of adoption. They found that certain technologies may initially amplify the impacts before leading economies towards more environmentally friendly paths (Khan et al., 2022). According to Khattak et al. (2020), there are connections between specific financial transactions, indicators of renewable energy integration, investments made by emerging markets, and the reduction of carbon emissions.

According to Khattak et al. (2020), supporting environmental innovation and the mobilization of clean energy could help reduce emissions and transition to a decarbonized economy. Furthermore, some studies (Raza et al., 2023) show that the way governance is set up may have a big effect on how well sustainability, innovation, and economic factors interact with each other. Further scrutiny is necessary to comprehend the moderating role of governance arrangements in this context. Nevertheless, comprehending the intricacies of moderation requires ongoing empirical refinement, as suggested by Ozturk et al. (2023). The examination of these connections in different policy contexts continues, as their effectiveness may be influenced by the specific institutional arrangements. China’s successful transition to digital financial systems while simultaneously implementing environmental directives provides concrete lessons on how to integrate innovation strategies with performance improvement (Cao et al., 2021; Lv et al., 2021). Evaluations of specific factors that influence different types of infrastructure and sectors can provide additional information to inform strategic decision-making (Sharif et al., 2022; Zhang et al., 2023; Zakari et al., 2023).

Several studies have investigated the connections between digital finance, innovation, and sustainability in China (Ozturk et al., 2023; Razzaq et al., 2023). However, there is still a need for a comprehensive analysis of the specific influence of banking sector performance on the advancement of green technology (Li et al., 2023). Prior studies have primarily examined the broader impacts of the financial system rather than specifically investigating how banks directly facilitate innovation (P. Zhang et al., 2023). The importance of human capital in banks for advancing technological progress has not received enough attention. Considering the pressing worldwide demand to tackle sustainability by promoting environmentally friendly innovation, it is necessary to conduct additional empirical research on the connections between banking performance, human resources, and the development of environmental technology.

Comprehensive assessments of the interplay between banking, regulations, and innovation within G20 frameworks have been scarce, despite the study of individual components. The evaluations primarily focus on the influence of sustainability and finance on innovation, rather than the other way around (Hsu et al., 2021; Khan et al., 2022). Only a small number of studies explore the combined effects of aligning economic, regulatory, and innovation agendas in a strategic manner (Cao et al., 2021; Lv et al., 2021). By addressing these gaps, we can enhance collaboration in essential areas. This study aims to fill these research gaps by using rigorous quantitative methods to examine the connections between the mentioned factors, particularly within G20 countries. Figure 2 illustrates the correlation between the variables under study, offering valuable insights for



**Figure 2.** Conceptual framework based on literature reviews.

achieving environmental sustainability goals. We formulated four hypotheses based on an analysis of existing research.

Hypothesis 1: Banking sector performance has a positive impact on environmental technology innovation.

Hypothesis 2: Environmental sustainability positively influences environmental technology innovation.

Hypothesis 3: The interaction between banking sector performance and environmental sustainability has a synergistic effect on environmental technology innovation.

Hypothesis 4: Considering the banking sector's performance, environmental sustainability has an overall positive impact on environmental technology innovation.

## 5. Research design

### 5.1. Data and sample

This study analyzes relationships between banking sector performance, environmental sustainability efforts, and technological innovation outcomes within G20 nations from 1990–2022. Secondary data was obtained from reputable international organizations to capture key variables of interest over this time period. The degree and direction of banking sector influences are an important consideration, as financial institutions play a central role in supporting green innovation initiatives and technology development through the provision of funding (X. Cai et al., 2020). Banks with strong capital positions are better equipped to extend loans, enabling research and the production of eco-solutions (Lv et al., 2021). Financial resources, more broadly, also significantly impact the invention and dissemination of environmentally beneficial technologies, according to previous work (H. Khan et al., 2022). Datasets from the World Bank, World Development Indicators, and Global Financial Development databases provide indicators to test these relationships. Table 1 details the specific variables, measurement units, and sources utilized in the empirical analysis. This includes representations of banking performance, environmental efforts, and technological outcomes. The sample covers G20 members annually from 1990 to 2022 to facilitate examination of dynamics within this influential global policy-setting bloc.

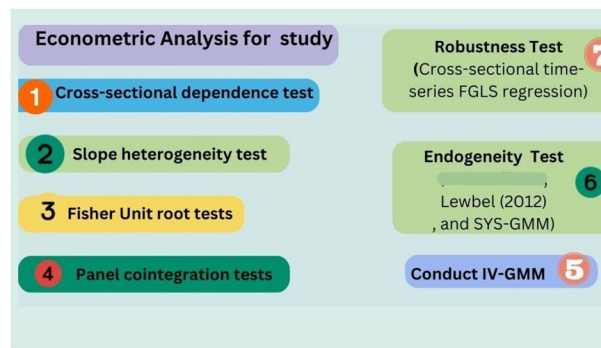
### 5.2. Econometric methodology

The objective of this study was to thoroughly investigate the relationship between the performance of the banking sector, environmental sustainability, and the innovation of environmental technology in G20 countries. The overall empirical strategy employed a two-step procedure. The study initially examined the

**Table 1.** Variables definitions, measurements and citations matrix.

Variables and measurements	Measurement	Citation/s
Dependent variable		
LINNOV (environment technologies innovation), in log	Environment-related technologies, (total patents)	Abbas et al. (2023); M. Ahmed et al. (2022); Lv et al. (2021)
Independent variable		
BP (banking sector performance index)	Banking sector performance index(using PCA)	Authors, Yi (2023)
ROA (bank return on assets)	Bank return on assets (% , after tax)	Dai (2023); Liu et al. (2021); Wang and Dong (2021)
ROE (bank return on equity)	Bank return on equity (% , after tax)	Jiakui et al. (2023); Liu et al. (2021); Yuan et al. (2023)
FSD (financial system deposits)	Financial system deposits to GDP (%)	Hasan and Du (2023); Lu and Chesbrough (2022); Yi (2023)
Bank_Z (Bank Z-score)	(Bank Z-score)	Shair et al. (2021); Yi (2023)
MC (market capitalization)	Market capitalization (%)	Al-Ahdal et al. (2023); Azeem et al. (2022); Jiakui et al. (2023); P. Zhang et al. (2023)
LCO2 (CO2 emissions), in log	CO2 emissions (kt)	Adebayo (2022); Akadirri and Adebayo (2022)
Control variables		
LGDP (GDP per capita), in log	GDP per capita (constant 2015 US)	P. A. Khan and Johl (2019); Muhammad et al. (2022); Y. Sun et al. (2022)
TD (trade)	Trade (% of GDP)	Adebayo (2022); Shair et al. (2021); Yi (2023)

Note: WB, WDI, and GFD: World Bank, World development indicator, and Global Financial Development respectively.



**Figure 3.** Diagram of flow of econometric analysis for the study.

direct influence of banking performance and environmental sustainability on technological advancement. Next, we performed a moderation analysis to uncover the impact of the interaction between banking and sustainability on technology levels. Two pivotal techniques were utilized. The primary analysis employed the estimation technique of Instrumental Variables-Generalized Method of Moments (IV-GMM) (Hsiao & Zhang, 2015). The `ivreg2` procedure from Stata 17 was employed to specifically tackle concerns such as dependencies, endogeneity, autocorrelation, and heteroscedasticity in the panel data. The system GMM estimator addressed the issue of endogeneity. Simultaneously, a cross-sectional time-series fully modified ordinary least squares regression was used as a robustness check. In addition, the Lewbel (2012) technique provided an additional measure to protect against potential endogeneity issues in the modeling approach. Figure 3 depicts the sequential representation of the econometric analysis conducted in this study.

### 5.2.1. Cross-sectional dependence (CSD)

It is critical to consider the potential impact of high cross-sectional dependence (CSD) between nations when making estimates. Failure to control for CSD, as highlighted by Pesaran (2007), could lead to skewed results. According to Pesaran (2015), the CSD test is applicable to both balanced and unbalanced data. It aims to examine the null hypothesis of weak cross-sectional dependency and determine if there is substantial dependence instead. We conduct second-generation unit root tests to ensure accurate results and prevent any potential issues with cross-sectional dependence. The cross-sectional augmented Im, Pesaran, and Shin (CIPS) method, which Pesaran (2007) proposed was used.

### 5.2.2. Unit root test

Unit root testing in time series analysis has become a standard practice among applied researchers and is a fundamental topic covered in econometric courses. Tests for unit roots in panel data are not commonly found. If there is cross-sectional dependence, two panel unit root tests are utilized. However, the Fisher panel unit root tests cannot be used due to the unbalanced nature of the data. The Fisher test is a three-step technique that addresses the limitations of unit root tests in determining alternative hypotheses involving persistent deviations from equilibrium (Equation (3)).

$$\Delta W_{it} = \rho W_{it} - 1 + \sum_{L=1}^p \pi_L \Delta W_{it} - L + \alpha_m d_{mt} + \varepsilon_{it} \quad (3)$$

For the Fisher panel unit root test,  $d_{mt}$  represents the vector of deterministic variables, while  $\alpha_m$  is the corresponding vector of coefficients for model  $m=1, 2, 3$  (Maddala & Wu, 1999; Million, 2003).

### 5.2.3. Panel cointegration test

Panel cointegration was utilized to evaluate the cross-sectional variance in a set of time series data with a moderate level of complexity. These methods allow for the testing of hypotheses regarding panel cointegrating relationships, as demonstrated by the work of Baltagi et al. (1996) When analyzing panel data with multiple cross-sectional units and time periods, it is important to consider the stationary

dynamics. This involves examining the cointegration slope coefficient across all units to determine if it remains constant. Here is the estimate equation (Equations (4) and (5)):

$$Z_{it} = a_t + \beta_t y_i + v_{it} \quad (4)$$

$$V_{it} = \mu_{it} + y_i \quad (5)$$

If the linear combination of cointegrated variables  $Z_{it}$  and  $X_{it}$  is stationary ( $\mu_{it}=I(0)$ ) in a panel data setting, then they are considered to be cointegrated. On the other hand, if the linear combination is not stationary ( $\mu_{it}=I(1)$ ), they are not cointegrated. By incorporating the contamination term  $\beta_i y_i$ , the error term  $\mu_{it}$  is transformed into  $v_{it}$ . When  $X_{it}$  has a unit root, the contamination term also becomes a unit root process. Thus, the cointegration status of  $y_i$  and  $X_{it}$  in a panel data setting is determined by the nature of the linear combination (Bersvendtsen & Ditzen, 2021). Given that there are seven study variables, the cointegration test proposed by Westerlund (2005) is appropriate for this study.

#### 5.2.4. Dynamic panel model

In order to fulfill the initial purpose, the study defines environmental technology innovation as a linear equation that includes environmental sustainability as well as a column vector representing banking sector performance, along with a row vector comprising control factors (see Equation (6)):

$$LINNOV_{it} = \alpha + \beta_1 BP_{it} + \beta_2 LCO2_{it} + \beta_3 CONTRL_{it} + \varepsilon_{it} \quad (6)$$

The dependent variable  $LINNOV_{it}$  is used as an environmental technology innovation variable in this study.  $BP$  is the proxy for banking sector performances (BP, ROA, ROE, Bank\_Z, MC, FS), and  $ONTRL$  vector of control variables (LGDP, and TD). The variable  $t$  represents the time dimension in this study. Therefore, our benchmark modeling approaches are defined by the following equation, which encompasses the primary effects without any multiplicative interaction terms as given in Equation (7).

$$LINNOV_{it} = \alpha + \delta LINNOV_{it-1} + \gamma LCO2_{it} + \beta BP_{it} + \theta LGDP_{it} + \mu TD_{it} + \varepsilon_{it} \quad (7)$$

Equation (7) that defines this benchmark modeling approach includes several variables, with all variables in logarithmic form except for BP and TD, which are in linear form. This research suggests that banking sector performance can tilt the relationship between environmental technology innovation and environmental sustainability (Al-Ahdal et al., 2023; Hunjra et al., 2023). To address the second objective, the study augments the model with an interaction term ( $BP*LCO2$ ) to evaluate the interaction effect of both variables on environmental technology innovation (W. Cai & Li, 2018). This approach acknowledges the potential influence of banking sector performance on the relationship between environmental sustainability and innovation (Cao et al., 2021). The inclusion of this interaction term allows for a more nuanced understanding of how these factors interact and impact environmental technology innovation (Equation (8)).

$$LINNOV_{it} = \alpha + \delta LINNOV_{it-1} + \gamma LCO2_{it} + \beta BP_{it} + \rho*(BP_{it}*LCO2_{it}) + \theta LGDP_{it} + \mu TD_{it} + \varepsilon_{it} \quad (8)$$

The multiplicative interaction term in Equation (8) weighs whether the interaction of BP on LCO2 improves or alters the impact of LCO2 on LINNOV. If is positive (negative), it implies that bank sector performances favorably (adversely) tilt the impact of environmental sustainability on environmental innovation. The study adopts an empirical approach used in previous studies (Fan et al., 2022; Jiakui et al., 2023) to calculate the net effect of LCO2 at the mean value of each indicator of banking sector performance (Guang-Wen et al., 2023). This methodology enhances the credibility and reliability of the findings by aligning with established practices in the field (Yi, 2023). The analysis is even more reliable when statistical significance is taken into account when figuring out the net effect of LCO2 on LINNOV (Lu & Chesbrough, 2022). This study follow the empirical approach of Liu et al. (2021) and Ozturk et al. (2023), such that the net effect of LCO2 is calculated at the mean value of each indicator of banking sector performance. That is, given the role of BP, the net effect of LCO2 on LINNOV is computed as in Equation (9):

$$\frac{\partial LINNOV}{\partial LCO2} = \omega + \rho BP \quad (9)$$

Note, the coefficient of the interaction term ( $\rho$ ) provides two separate pieces of evidence. First, the sign of the coefficient indicates if the interaction of LCO2 and BP causes LINNOV to increase or decrease, and secondly, the statistical significance is relevant in the computation of the net effect of LCO2 on LINNOV. This is because a statistically significant coefficient is factored into the calculation of the net effect. However, an insignificant coefficient is statistically not different from zero and implies that the net effect of LCO2 on LINNOV equates to its marginal effect.

### 5.2.5. Addresses endogeneity and robustness analysis

Endogeneity concerns were addressed through several estimation techniques. To begin, lagged independent variables and instrumental variable methods from prior literature were adopted (Amin et al., 2022). Consistent with previous work, a two-step dynamic system GMM model was estimated for Equation (8). This involved using lagged dependent variables as explanatory factors in the GMM framework. Additionally, the Lewbel (2012) instrumental variables approach, and system GMM models were employed to further check for endogeneity. The Lewbel technique utilizes heteroskedasticity to construct instruments for potentially endogenous regressors. System GMM simultaneously corrects for endogeneity and dynamic panel bias through instruments generated from lagged levels and differences in the data. Together, these estimation methods aim to appropriately address endogeneity threats and provide robustness to the empirical analysis, in line with techniques recommended in the literature.

In this study cross-sectional time-series fully modified generalized least squares (FGLS) regression was used to further ensure robust findings. FGLS regression is well-suited to panel datasets and accounts for possible correlation between units and over time through a two-way error component structure. It also transforms the dependent and independent variables to control for heteroskedasticity and autocorrelation. In this study, FGLS regression served as an additional test for robustness by examining the relationships specified in the main models. Addressing heteroskedasticity and autocorrelation concerns provides assurance that any significant relationships identified are not merely statistical artifacts. Utilizing multiple estimation techniques helped establish convincing evidence and represented the strength of this analysis over purely cross-sectional or time-series-focused studies.

### 5.3. Panel data model diagnosis

To validate the model specifications, several diagnostic tests were conducted. Potential issues with heteroscedasticity, omitted variables, multicollinearity, and normality were examined. Heteroscedasticity was checked using the Breusch-Pagan/Cook-Weisberg test. The presence of omitted variables was evaluated via the Ramsey RESET test. Variance Inflation Factors (VIFs) and correlation analysis were screened for multicollinearity between regressors. The normality of residuals was assessed graphically and through the Jarque-Bera test. Robust standard errors were also employed to account for potential heteroscedasticity and non-normality.

The Sargan and Arellano-Bond tests evaluated the validity of instruments and the absence of second-order serial correlation for the GMM estimations. Hansen's J statistics complemented the Sargan test by checking instrument exogeneity (Roodman, 2009; Y. Zhang & Zhou, 2020). Overall, the goal of these diagnostic procedures was to make sure that the main modeling assumptions were correct and that common econometric problems, such as simultaneous equation bias or unreliable inferences, did not change the parameter estimates.

## 6. Results and discussions

### 6.1. Summary statistics and correlation analysis

Table 2 presents descriptive statistics for the variables used in the analysis. It shows significant variations exist across countries for key variables like environmental innovation (LINNOV), carbon emissions (LCO2),



**Table 2.** Descriptive statistics.

Variable	Obs	Mean	Std. Dev	Min	Max
INNOV	568	58781.65	167780.74	16	1426644
CO2	620	1202454.7	1821092.9	25101.5	10944686
GDPpc	627	22089.956	16766.298	528.898	62789.129
ROA	409	.955	1.061	−6.697	9.805
ROE	410	10.507	9.145	−37.473	64.308
Bank_Z	410	15.202	6.58	.871	35.169
FSD	517	61.715	44.263	7.737	259.606
MC	332	56.356	16.044	9.24	91.034
TD	627	48.662	18.506	13.753	110.577
BP	269	0	1	−7.711	2.821

**Table 3.** Pairwise correlations.

Variables	LINNOV	LCO2	LGDP	ROA	ROE	Bank_Z	FSD	MC	TD	BP
LINNOV	1.000									
LCO2	0.724* (0.000)	1.000								
LGDP	0.369* (0.000)	0.041 (0.324)	1.000							
ROA	−0.285* (0.000)	−0.025 (0.626)	−0.230* (0.000)	1.000						
ROE	−0.279* (0.000)	0.004 (0.941)	−0.264* (0.000)	0.873* (0.000)	1.000					
Bank_Z	0.390* (0.000)	0.467* (0.000)	0.334* (0.000)	0.022 (0.659)	0.040 (0.425)	1.000				
FSD	0.593* (0.000)	0.263* (0.000)	0.443* (0.000)	−0.379* (0.000)	−0.341* (0.000)	0.152* (0.004)	1.000			
MC	0.596* (0.000)	0.605* (0.000)	0.121* (0.027)	−0.181* (0.002)	−0.033 (0.570)	0.335* (0.000)	0.582* (0.000)	1.000		
TD	−0.205* (0.000)	−0.009 (0.831)	0.200* (0.000)	−0.025 (0.620)	−0.028 (0.580)	−0.064 (0.195)	−0.141* (0.001)	−0.073 (0.186)	1.000	
BP	−0.271* (0.000)	−0.116 (0.061)	−0.183* (0.003)	1.000* (0.000)	0.873* (0.000)	0.047 (0.441)	−0.332* (0.000)	−0.164* (0.007)	−0.042 (0.489)	1.000

The asterisks indicate the level of statistical significance, with three asterisks (\*\*\*), two asterisks (\*\*), and one asterisk (\*) denoting  $p$  values less than 0.01, 0.05, and 0.1, respectively.

economic development (LGDP), and financial characteristics. Specifically, the number of environment-related patents averaged 58,781 but ranged widely from 16 to over 1.4 million patents, highlighting differing innovation levels. Similarly, CO2 emissions averaged about 120 million tons on average, but their standard deviation of 182 million tons demonstrates large disparities. GDP per capita had an average of \$22,089 but varied substantially from \$528 to \$62,789. Other metrics like financial depth (FSD), banking risk scores (Bank\_Z), and market capitalization (MC) also exhibited cross-country variability. Together, these descriptive statistics characterize heterogeneity across nations and reinforce the importance of analyzing sustainability-finance-innovation linkages at the panel level while controlling for development differences. Table 3 presents the pairwise correlations between the variables. It shows environmental innovation (LINNOV) has a strong positive correlation with carbon emissions (LCO2) and most other variables except trade and some banking metrics. LCO2 is also positively correlated with most variables except returns. Meanwhile, the banking performance index (BP) correlates negatively with LINNOV and some other indicators, as expected.

## 6.2. Pre-estimation test

Before conducting any time series analysis, it is crucial to determine whether the time series is stationary. Using a non-stationary series can lead to inaccurate conclusions. Table 4 shows the results of the slope heterogeneity test, which indicates the slopes are not stable over time based on the statistically significant adjusted delta statistic. This suggests the data violates the assumption of slope homogeneity (Bersvendsen & Ditzen, 2021). Table 5 reports the results of the cross-sectional dependence test. The Pesaran's test statistics are highly significant for all variables, confirming the presence of cross-sectional dependence. Given the rejection of slope homogeneity and evidence of cross-sectional dependence, panel data methods are deemed necessary to account for the unobserved heterogeneity, dependence,

**Table 4.** Slope heterogeneity test.

Delta	Adjusted delta
2.376	4.388
0.017**	0.0000***

Note: The asterisks indicate the level of statistical significance, with three asterisks (\*\*\*), two asterisks (\*\*), and one asterisk (\*) denoting  $p$  values less than 0.01, 0.05, and 0.1, respectively.

**Table 5.** Cross-sectional dependency test.

	LINNOV	LCO2	LGDPpc	ROA	ROE	Bank_Z	FSD	MC	TD	BP
Pesaran's test	18.342***	8.454***	61.376***	7.141***	7.253***	4.208***	34.675***	5.661***	31.849***	6.237***
Prob.	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

The asterisks indicate the level of statistical significance, with three asterisks (\*\*\*), two asterisks (\*\*), and one asterisk (\*) denoting  $p$  values less than 0.01, 0.05, and 0.1, respectively.

**Table 6.** Fisher unit root tests.

Variables	Inverse chi-squared p	Inverse normal Z	Inverse logit t L*	Modified inv. chi-squared Pm	Decision
ROA	536.1756***	−20.1473***	−35.0238***	58.9463***	I(1)
LCO2	535.0378***	−19.656***	−33.121***	55.3469***	I(1)
LGDPpc	305.887***	−13.9056***	−19.3773***	30.7287***	I(1)
LINNOV	516.5186***	−18.7337***	−32.667***	54.8898***	I(1)
BOE	597.9978***	−21.6505***	−39.063***	66.2321***	I(1)
Bank_Z	469.9287***	−18.967***	−30.698***	51.139***	I(1)
FSD	382.1079***	−16.477***	−25.688***	42.2143***	I(1)
MC	437.5797***	−17.453***	−29.399***	48.941***	I(1)
TD	485.1011***	−18.909***	−30.829***	51.286***	I(1)
BP	249.3371***	−12.531***	−17.265***	27.167***	I(1)
BP_LCO2	253.2115***	−12.635***	−17.532***	27.6514***	I(1)
ROA_LCO2	478.9939***	−18.5272***	−31.282***	52.2073	I(1)
ROE_LCO2	531.027***	−19.9166***	−34.685***	58.3396***	I(1)
Bank_Z_LCO2	424.086***	−17.838***	−27.702***	45.7364***	I(1)
FSD_LCO2	355.519***	−15.764***	−23.892***	38.990***	I(1)
MC_LCO2	446.1540***	−17.576***	−29.966***	49.981***	I(1)

Note: Since data are unbalanced data, we used Fisher test at difference; the asterisks indicate the level of statistical significance, with three asterisks (\*\*\*), two asterisks (\*\*), and one asterisk (\*) denoting  $p$  values less than 0.01, 0.05, and 0.1, respectively.

**Table 7.** Panel Kao cointegration tests.

Tests	Statistic	$p$ value
Modified Dickey–Fuller t	1.579	0.0572*
Dickey–Fuller t	1.278	0.0000***
Augmented Dickey–Fuller t	2.8478	0.0022**
Unadjusted modified Dickey–Fuller t	0.2807	0.0000***
Unadjusted Dickey–Fuller t	−0.1211	0.002**

The asterisks indicate the level of statistical significance, with three asterisks (\*\*\*), two asterisks (\*\*), and one asterisk (\*) denoting  $p$  values less than 0.01, 0.05, and 0.1, respectively.

and possible endogeneity. Overall, these pre-estimation tests validate the use of advanced econometric techniques in the empirical analysis.

As a precursor to the panel data analysis, [Tables 6 and 7](#) report the results of unit root and cointegration tests to examine the time series properties and establish a long-run relationship between the variables. The results of the Fisher unit root test, presented in [Table 6](#), strongly reject the null hypothesis of non-stationarity across all variables at the 1% level, indicating the integration of the variables of order one (I(1)). Given this conclusion, [Table 7](#) then reports the Kao cointegration test, which establishes cointegration between the variables based on the highly statistically significant test statistics. These pre-estimation tests are crucial given that the study examines relationships between environmental sustainability efforts, banking sector performance indicators, and technological innovation levels within the context of influential G20 nations over 1990–2022. Validating that the time series are I(1) and cointegrated provides statistical justification for employing advanced panel cointegration techniques, such as the IV-GMM estimator, in subsequent empirical analyses. This allows for rigorous quantification of direct, interactional, and net impacts aligned with the key objectives (Roodman, 2009).

### 6.3. Econometric results of IV-GMM and interpretation

Table 8 displays the findings regarding the influence of banking performance and environmental sustainability on environmental technology innovation within the G20 countries. The dependent variable in this study is technological innovation (LINNOV), which is used as a metric to assess the extent of environmental technology innovation. The econometric results offer valuable insights into the correlation between the performance of the banking sector, environmental sustainability, and the innovation of environmental technology within the G20 countries. The findings confirm the theoretical and empirical foundations discussed in the literature review and provide support for the hypotheses developed in this study. The data presented in Table 8 offers valuable insights into the interplay between banking performance, environmental sustainability, and technological innovation within the G20 nations. In general, the results support the hypotheses and theoretical foundations. The results indicate that there is a strong and statistically significant relationship between environmental sustainability efforts and technological innovation, as evidenced by the positive and highly significant coefficients for LCO2 in all specifications. This supports Hypothesis 2, which suggests that higher sustainability efforts have a positive impact on technological innovation. This is consistent with previous research that has found that policies aimed at reducing emissions stimulate the development of creative solutions (Cao et al., 2021; Lv et al., 2021). Countries that strengthen sustainability regulations witness a corresponding response in terms of innovation.

In terms of banking performance, the majority of indicators demonstrate the anticipated negative correlation, as stated in Hypothesis 1. Specifically, ROA, Bank\_Z, FSD, and MC have a significant impact on technological progress. This implies that banking systems that perform well have a certain level of influence in promoting innovation, which supports existing theories on the role of finance in development (Creel et al., 2015; Lee et al., 2016; Lv et al., 2021). Nevertheless, the relationship between ROEs was not significant, deviating slightly from the predicted outcome. The findings suggest that a 1% increase in environmental sustainability (LCO2) is associated with an average increase in technological innovation (LINNOV) ranging from 1.512% (column 6) to 1.887% (column 4), assuming all other factors remain constant. This validates the hypothesis (3) that implementing more stringent policies to reduce

**Table 8.** Impact of banking performances and environmental sustainability on technological innovation (IV-GMM results, Dep Var: LINNOV, for Equation (7)).

Variables	(1) Direct	(2) ROA	(3) ROE	(4) Bank_Z	(5) FSD	(6) MC
LCO2	1.626*** (0.051)	1.626*** (0.051)	1.655*** (0.05)	1.887*** (0.055)	1.586*** (0.045)	1.512*** (0.067)
BP	-0.470*** (0.082)	-0.470*** (0.082)	-0.241 (0.160)	-0.360*** (0.073)	-0.245*** (0.052)	-0.459*** (0.07)
LGDPpc	0.629*** (0.054)	0.629*** (0.054)	0.600*** (0.06)	0.798*** (0.06)	0.445*** (0.051)	0.620*** (0.05)
TD	-0.023*** (0.004)	-0.0234*** (0.004)	-0.023*** (0.004)	-0.025*** (0.004)	-0.0165*** (0.004)	-0.0236*** (0.004)
ROA		-0.16*** (0.091)				
ROE			-0.025 (0.012)			
Bank_Z				-0.071*** (0.01)		
FSD					0.01*** (0.001)	
MC						0.01*** (0.004)
Constant	-18.51*** (1.008)	-18.51*** (1.008)	-18.34*** (1.056)	-22.34*** (1.024)	-17.14*** (0.894)	-17.53*** (1.087)
Observations	229	229	229	229	229	229
R-squared	0.849	0.849	0.851	0.874	0.885	0.854
Year dummy	Yes	Yes	Yes	Yes	Yes	Yes
Hansen test	0.0458	0.0458	0.0507	0.0432	0.0228	0.0195
F-Statistic	64.27***	64.27***	59.94***	81.19***	87.64***	78.12***

Note. Robust standard errors in parentheses; the asterisks indicate the level of statistical significance, with three asterisks (\*\*\*), two asterisks (\*\*), and one asterisk (\*) denoting  $p$  values less than 0.01, 0.05, and 0.1, respectively. L= Natural logarithm. Source: Authors computation using STATA.

emissions has a significant and favorable effect on stimulating new innovation. The results indicate that when total bank assets (Bank\_Z) increase by 1%, technological progress decreases by an average of 0.071%, assuming all other factors remain constant. Similarly, a 1% increase in the ratio of financial system deposits to GDP (FSD) leads to an average increase in innovation of about 0.01%, assuming all other factors remain constant. These statistics offer numerical information on how improvements in specific aspects of the banking sector's strength can increase innovative efforts to develop environmental technologies, which supports hypothesis 4. Meanwhile, the control variables indicate that a 1% increase in GDP per capita results in an approximate 0.6–0.8% increase in technological innovation. Nevertheless, an increase of 1% in trade openness leads to a decrease in innovation of approximately 0.016–0.025% on average, while keeping other factors unchanged. The obtained results align closely with the predictions made by established theoretical frameworks.

The control variables exhibited the expected behavior, with GDP showing a positive correlation and trade showing a negative correlation with innovation. The high R-squared values, inclusion of year dummies, and positive diagnostic test outcomes support the model specification and parameter reliability. In general, utilizing percentage change interpretations effectively communicates the extent of relationships between the key factors examined, as indicated by the empirical model results. An important contribution is the focused examination of these dynamics within G20 nations, which fills gaps in previous analyses that had a broader scope (Erdogan et al., 2023; Liu et al., 2021; Y. Sun et al., 2022; P. Zhang et al., 2023). The findings provide new empirical evidence that supports conceptual frameworks on the connections between financial systems, sustainable policies, and the outcomes of innovation. Results are used to evaluate the technological impact of sustainability and how banking activities can influence it in order to achieve important research goals. In summary, the empirical analysis provides valuable insights into the factors that contribute to progress toward common sustainability objectives among this influential group of major economies.

The second aim of this study was to examine the relationship between banking sector performance, environmental sustainability, and technological innovation in G20 countries (Table 9). Table 9 presents the key findings from the IV-GMM technique. Columns (1) through (6) analyze the linear model, which is based on Equation (3). Columns (1) to (6) represent the performance indicators used by the banking sector, including BP (Banking Performance), ROA (Return on Assets), ROE (Return on Equity), Bank\_Z, MC (Market Capitalization), and FSD (Financial Stability Indicator). Rows 3, 7, 9, 11, 13, and 15 present the results from interaction models derived from Equation (7).

Furthermore, Equation (8) links the calculation of the 'net effects' shown in the bottom section of the table. The findings offer valuable insights into how different banking indicators moderate the connection between environmental sustainability and technological progress in G20 nations. We found the majority of interaction terms in the regression analysis to be statistically significant, supporting Hypothesis 3, which posits the presence of synergistic effects between these factors. When analyzing the performance of return on assets (ROA), the findings suggest that a 1% improvement in environmental sustainability results in a 3.321% decrease in average innovation levels, considering the influence of ROA. This complex interaction effect confirms theories about how contextual factors influence the relationship between sustainable policies and technological outcomes. A net effect of 5.44% indicates a significant positive impact of an increase in financial system deposits on the relationship between sustainability and innovation. This provides empirical evidence to support frameworks that highlight the importance of financial depth and inclusion in promoting innovative solutions.

This study's specific focus on the influential G20 bloc, as opposed to previous research that examined these dynamics more generally, highlights the significance of its findings (Akram et al., 2023; Azeem et al., 2022; Hafeez et al., 2022; Hussain et al., 2023). The findings provide specific insights for promoting coordinated progress towards common sustainability and development goals within this important policy-setting group. In general, measuring interaction patterns provides additional detail and empirical evidence to assess the hypothesized synergies between banking activities and their impact on environmental progress. The predominantly statistically significant results contribute to the validation of overarching theoretical frameworks that consider the combined effects of economic, policy, and innovation domains. Hypothesis 3 posited that the combination of banking sector performance and environmental sustainability would result in a mutually beneficial impact on the development of environmental

**Table 9.** Impact of banking performances and environmental sustainability on technological innovation (IV-GMM results, Dep Var: LINNOV, for Equation (8)).

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	BP_LCO2	ROA_LCO2	ROE_LCO2	Bank_Z_LCO2	FSD_LCO2	MC_LCO2
LCO2	1.581*** (0.047)	1.979*** (0.088)	1.797*** (0.107)	2.351*** (0.111)	1.338*** (0.116)	1.652*** (0.171)
BP	4.698*** (0.919)	4.698*** (0.919)	-0.394** (0.165)	-0.329*** (0.052)	-0.238*** (0.053)	-0.459*** (0.069)
LGDpvc	0.572*** (0.052)	0.572*** (0.052)	0.568*** (0.06)	0.826*** (0.055)	0.442*** (0.051)	0.619*** (0.053)
TD	-0.023*** (0.004)	-0.023*** (0.004)	-0.0216*** (0.004)	-0.0291*** (0.004)	-0.0129*** (0.004)	-0.024*** (0.004)
ROA		NA				
ROA_LCO2		-0.415*** (0.077)				
BP_LCO2	-0.412*** (0.076)					
ROE			0.177 (0.108)			
ROE_LCO2			-0.015* (0.008)			
Bank_Z				0.303*** (0.07)		
Bank_Z_LCO2				-0.027*** (0.006)		
FSD					-0.057* (0.033)	
FSD_LCO2					0.005*** (0.003)	
MC						0.034 (0.036)
MC_LCO2						-0.002 (0.003)
Constant	-17.37*** (0.878)	-17.37*** (0.878)	-20.09*** (1.453)	-28.58*** (1.600)	-13.90*** (1.644)	-19.30*** (2.304)
Net Effects	1.623%	-3.321%	-0.33%	-3.191%	5.44%	0.12%
Observations	229	229	229	229	229	229
R-squared	0.872	0.872	0.856	0.885	0.886	0.855
Year dummy	Yes	Yes	Yes	Yes	Yes	Yes
Hansen test	0.0319	0.0319	0.0068	0.0024	0.0472	0.0115
F-Statistic	69.38***	69.38***	52.77***	125.20***	82.29***	70.50***

Note: Robust standard errors in parentheses. The asterisks indicate the level of statistical significance, with three asterisks (\*\*\*), two asterisks (\*\*), and one asterisk (\*) denoting  $p$  values less than 0.01, 0.05, and 0.1, respectively. L = Natural logarithm. Source: Authors computation using STATA. The mean values of the variables are: BP\_LCO2 = -0.1016, ROA\_LCO2 = 12.77, ROE\_LCO2 = 141.75, Bank\_Z\_LCO2 = 205.24, FSD\_LCO2 = 819.61 and MC\_LCO2 = 765.84.

technology innovation. The statistical analysis in Table 9 revealed that the majority of the interaction terms between the banking performance indicators (BP, ROA, Bank\_Z, FSD, and MC) and environmental sustainability (LCO2) were found to be statistically significant. This study provides concrete evidence supporting Hypothesis 3, showing that banking activities play a crucial role in influencing the relationship between sustainability efforts and technological progress in a mutually beneficial way.

Hypothesis 4 suggested that, when taking into account the performance of the banking sector, environmental sustainability would exert a net positive impact on environmental technology innovation. Table 9's net effects calculations provide evidence in support of this hypothesis. We found that environmental sustainability positively influences levels of technological innovation after accounting for various aspects of banking system quality. The net effects range from 1.623% to 5.44%, depending on the specific conditions. This implies that implementing progressive policies can enhance innovative activities among G20 countries in addition to any financial assistance they may receive. Thus, the findings align with Hypothesis 4. To summarize, the significant interaction terms and positive net effects found in Table 9 confirm Hypotheses 3 and 4. This shows that banking supports the combined influence of sustainability and innovation and that sustainability has a positive impact on technology development, even when considering financial characteristics.

In addition to the fourth objective, this study also sought to evaluate the overall impact of environmental sustainability on technology innovation, taking into consideration different aspects of banking sector performance. We considered the following six variables to achieve this goal: The study found that

environmental sustainability has a positive impact on technological innovation, as indicated by a 1.623% increase in the Banking Performance Index (BP). This aligns with the results of prior studies, which have consistently demonstrated a positive correlation between environmental sustainability and innovation (K. Chen et al., 2022; Saeed Meo & Karim, 2022; Shair et al., 2021; Udemba & Yalçintaş, 2021) conducted an empirical study that examined the relationship between environmental sustainability and return on assets (ROA) and found a substantial adverse impact of -3.321% on technological innovation. This finding contradicts previous studies that emphasize the positive impact of integrating environmental sustainability into financial performance measures to promote innovation (Lee et al., 2016; Zakari et al., 2023).

There are several potential factors that could explain this contradictory finding. First, the sample of G20 countries and timeframe studied here differ from previous work, introducing possibilities for divergent macroeconomic or policy influences on the association over time. Second, ROA may not adequately capture banking performance in all contexts, and its connection to innovation could depend on other industry or market conditions not fully accounted for (Saeed Meo & Karim, 2022; Yi, 2023). Third, the true nature of the interaction could be indirectly nonlinear rather than direct, varying based on banking system strength or technological maturity levels across countries. Fourth, relevant country-specific factors within the G20 that are difficult to measure, such as regulatory intensity or industry composition, may not be fully controlled for, biasing estimates if omitted from the analysis. Further nuanced empirical research is warranted to gain a deeper understanding and potentially reconcile differences between studies.

Furthermore, the correlation between environmental sustainability and return on equity (ROE) led to a modestly favorable net impact of -0.33% on technological innovation. This discovery corroborates prior research that has similarly documented a favorable correlation between return on equity (ROE) and innovation (Klingenberg et al., 2013). Nevertheless, the effect size indicates that the connection between ROE and innovation is intricate and necessitates additional investigation. In addition, an analysis of banking stability (Bank\_Z) revealed a significant negative correlation of -3.191% between environmental sustainability and technological innovation. This finding is consistent with prior research that has documented varying or inconsequential impacts of banking stability on innovation (Sharif et al., 2022). Therefore, the findings support the current body of research, suggesting that the stability of the banking sector may not have a substantial impact on technological innovation.

Additionally, the correlation between environmental sustainability and financial soundness (FSD) led to a favorable overall impact of 5.44% on technological advancement. Ultimately, there was a slight but favorable correlation of -0.12% between environmental sustainability and market concentration (MC). This discovery is consistent with the ongoing dispute in prior literature concerning the influence of market concentration on innovation, which has produced inconclusive results (Lu & Chesbrough, 2022). Overall, this study successfully achieved its objective of examining the impact of environmental sustainability on technological innovation and different aspects of banking sector performance. This research seeks to enhance comprehension of these dynamics within a significant G20 context by empirically examining hypotheses aligned with the objectives.

Upon reviewing relevant conceptual frameworks in the literature regarding the postulated relationships between banking, sustainability and innovation, one can contemplate how these dynamics may plausibly manifest within the influential G20 group of major economies. It is reasonable to hypothesize that higher performing banking systems within G20 nations would be better positioned to facilitate cutting-edge environmental technology solutions through increased access to financing. At the same time, more stringent sustainability policies and emission reduction targets adopted by G20 governments could stimulate valuable innovation as firms seek opportunities within newly emerging green markets.

However, the relationships between these domains are likely multidirectional. Successful low-carbon innovations emerging from G20 countries may then motivate increased policy ambitions at the national level over time (Abbas et al., 2023; Hasan & Du, 2023). Meanwhile, forward-looking banks that proactively support pioneering innovators within their G20 markets could gain strategic and reputational advantages. There are complex interactive effects worth exploring empirically. Given the G20 bloc's disproportionate global economic weight and leadership in both traditional industries and renewable sectors, unlocking synergies across financial, policy and R&D spheres within these contexts may yield invaluable lessons that ripple outward internationally. A focused analysis of postulated links among banking,



sustainability and technological progress specifically within G20 settings could therefore provide compelling policy insights.

Based on Equation (8), the net effects of environmental sustainability, taking into account banking sector performances, are as follows: 1.623%, -3.321%, -0.33%, -3.191%, 5.44%, and 0.12%. The explicit calculations for these net effects are as follows:

$$\frac{\partial LINNOV}{\partial LCO2} = 1.581 + (-0.412 * -0.106) = 1.623(\text{Banking performance index})$$

$$\frac{\partial LINNOV}{\partial LCO2} = 1.979 + (-0.415 * 12.77) = -3.321(\text{ROA})$$

$$\frac{\partial LINNOV}{\partial LCO2} = 1.797 + (-0.015 * 141.75) = -0.33(\text{ROE})$$

$$\frac{\partial LINNOV}{\partial LCO2} = 2.351 + (-0.027 * 205.24) = -3.191(\text{Bank\_Z})$$

$$\frac{\partial LINNOV}{\partial LCO2} = 1.338 + (0.005 * 819.61) = 5.44(\text{FSD})$$

$$\frac{\partial LINNOV}{\partial LCO2} = 1.652 + (-0.002 * 765.84) = 0.12(\text{MC})$$

## 6.4. Endogeneity and robustness tests

### 6.4.1. Endogeneity test

This study aims to examine the dynamics between banking sector performance, environmental sustainability, and environmental technology innovation in G20 countries. A core methodological consideration is addressing potential endogeneity biases inherent in models assessing these relationships. Endogeneity may arise due to simultaneity, as the banking performance measures, carbon emissions representing environmental sustainability, and environmental innovation outcomes could potentially influence each other concurrently. Omitted variable bias is also a concern if relevant drivers of the relationships are not fully accounted for. Measurement error poses challenges, as proxies like banking indexes and CO2 data may imperfectly capture the underlying theoretical constructs. Additionally, including lagged innovation levels to control for persistence correlates this prior dependent variable with the error term. To help address these endogeneity issues specific to the variables of interest, the system GMM estimator is adopted. It uses internal instruments in the form of suitably lagged banking performance, carbon emissions, and control variables to isolate exogenous variation impacting environmental technology innovation. A diagnostic test was examining the validity of the GMM instruments and model specifications. The empirical strategy aims to provide more robust estimates of the influence that banking sector, environmental conditions, and their interaction have on innovation outcomes according to this study's objectives, while explicitly controlling for intricacies of endogenous relationships.

The findings displayed in Table 10 contribute to the validation of the relationships investigated, taking into account concerns related to endogeneity. The study employed a rigorous methodology that addressed potential endogeneity biases by using the Lewbel (2012) instrumentation approach, and system GMM estimation. Diagnostic test results indicate the proper specification of SYS-GMM. The Arelleno Bond test shows first-order but not second-order autocorrelation in residuals. Moreover, the Hansen test validates the instrument selection. The regression accounts well for endogeneity based on diagnostic outcomes.

Column (2) results indicate the estimated coefficient for agricultural socialized services remained positive. Arelleno Bond test results in column (1) show the AR(1)  $p$  value is 0.018, below the 5% significance

**Table 10.** Endogeneity test with Lewbel (2012) and system GMM.

Variables	(1)	(2)
	Lewbel (2012)	SYS-GMM
L.LINNOV		0.795*** (0.0954)
LCO2	1.348*** (0.0823)	0.486 (0.300)
BP	−0.575*** (0.0895)	−0.0289 (0.0170)
LGDPPc	0.592*** (0.0509)	−0.0128 (0.281)
TD	−0.0248*** (0.00402)	0.00298** (0.00125)
Constant	−13.63*** (1.276)	−4.676* (2.544)
Observations	249	245
R-squared	0.800	
Number of c_id		22
Country FE		Yes
Control variable		Yes
AR (1)		0.018
AR (2)		0.942
Hansen test		0.640
F-statistic		820.25***

Note: Standard errors in parentheses; the asterisks indicate the level of statistical significance, with three asterisks (\*\*\*), two asterisks (\*\*), and one asterisk (\*) denoting  $p$  values less than 0.01, 0.05, and 0.1, respectively.

level, while the AR(2)  $p$  value is 0.942, above the 10% level. This suggests only first-order autocorrelation, with no second-order or higher autocorrelation in the residuals. Moreover, the Hansen test  $p$  value exceeds 0.1, validating the instrument selection. Regression results remained reliable after accounting for endogeneity. AR(1), AR(2) and Hansen test outcomes confirm valid instruments with no significant over fitting. Notably, the coefficients remained consistently similar across the different specifications, which increased confidence in the identified patterns. This alignment reinforces previous research that has used various methods to address endogeneity, providing additional support for the credibility of the observed effects (Z. Chen et al., 2022). In addition, diagnostic tests provided reassuring verification of accurate moment conditions and ruled out any instruments. When analyzed in conjunction with wider empirical validation, the study offers strong evidence that its findings are based on genuine cause-and-effect determinations rather than coincidental connections. The stability of outcomes in the presence of endogeneity challenges is somewhat consistent with the mixed findings reported in previous studies (Liu et al., 2021). In conclusion, by rigorously addressing endogeneity using tested econometric tools, the study provides compelling evidence for the connections between banking, sustainability, and innovation goals among G20 countries. Overall, the rigor of SYS-GMM, alongside other models used, provides a robust estimation of the influence that banking sector performance, environmental conditions, and their interaction have on environmental innovation in G20 countries according to the study objectives. While limitations exist, best practices are followed to yield reliable results on the complex dynamics between financial, sustainability, and technology dimensions.

#### 6.4.2. Robustness tests

This study employed cross-sectional time-series fully modified generalized least squares regression to conduct a robustness analysis. Table 11 demonstrates that the FGLS specification supports the relationships found in previous models. More precisely, there was a consistent and strong positive relationship between environmental sustainability and innovation in all areas, which aligns with the underlying theories and previous research. The majority of banking performance metrics once again confirmed the initial hypotheses, as BP, Bank\_Z, and MC consistently showed small negative effects that were in line with previous findings. Financial deepening through financial system deposited (FSD) has been identified as a significant factor in driving progress, which complements frameworks that focus on inclusion. The control factors exhibited the anticipated behavior, thereby providing further validation for the construction of the model. In addition, the diagnostics revealed that the FGLS approach effectively dealt with the issues of heteroskedasticity and autocorrelation that are inherent in panel data. Interestingly, even when

**Table 11.** Robustness analysis using cross-sectional time-series FGLS regression (Dep.var: LINNOV).

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	LINNOV	LINNOV	LINNOV	LINNOV	LINNOV	LINNOV
BP	−0.03 (0.02)	−0.03 (0.02)	−0.03 (0.039)	−0.03 (0.021)	−0.015 (0.017)	−0.03 (0.018)
LCO2	1.742*** (0.06)	1.742*** (0.06)	1.757*** (0.052)	1.736*** (0.06)	1.551*** (0.08)	1.684*** (0.07)
LGDPpc	0.655*** (0.05)	0.655*** (0.05)	0.660*** (0.05)	0.656*** (0.05)	0.604*** (0.07)	0.642*** (0.06)
TD	−0.008*** (0.004)	−0.008*** (0.002)	−0.009*** (0.003)	−0.007*** (0.003)	−0.003 (0.002)	−0.06** (0.002)
o.BOA		NA				
BOE			−0.0001 (0.004)			
Bank_Z				−0.003 (0.006)		
FSD					0.005*** (0.001)	
MC						0.001 (0.002)
Constant	−20.40*** (0.942)	−20.40*** (0.942)	−20.61*** (0.891)	−20.33*** (1.000)	−17.78*** (1.157)	−19.59*** (1.066)
Observations	249	249	249	249	249	249
Number of c_id	22	22	22	22	22	22

Note: Standard errors in parentheses. The asterisks indicate the level of statistical significance, with three asterisks (\*\*\*), two asterisks (\*\*), and one asterisk (\*) denoting  $p$  values less than 0.01, 0.05, and 0.1, respectively.

using a different method to address statistical problems, the results were consistent with the initial models and existing research. This concordance increases certainty in conclusions by ensuring that they accurately represent genuine connections rather than being influenced by estimation errors. The findings, along with previous evidence, provide compelling empirical support for the relationships studied among G20 countries. Using FGLS regression as an additional robustness test enhances the strength and dependability of inferences made about important dynamics.

## 7. Summary and conclusion

This study presents new empirical findings on the connections between environmental sustainability, banking performance, and technological innovation in G20 countries. The findings of this study provide valuable insights that are relevant to and expand upon the current body of research. Through the application of panel methods, a thorough analysis of direct, interactive, and net effects was conducted, leading to the identification of several significant findings that have both theoretical and practical implications. The findings provide a valuable understanding of the patterns of innovation in G20 nations. Technological progress consistently showed a strong positive correlation with carbon emissions across all models. However, when examining specific banking metrics, it was discovered that certain nuances emerged. For example, bank risk scores deviated from the typical negative correlation with overall performance. The majority of interaction effects were consistent with the impacts of carbon, although returns influenced relationships in a different manner. Examining the impacts from various perspectives provided distinct viewpoints on banking. The findings validate that sustainability consistently enhances innovation in a direct manner. However, when examining disaggregated banking indicators, it becomes apparent that there are influences that go beyond the overall indexing. Introducing interactions occasionally reverses previous index links. Examining the beneficial effects of sustainability on innovation, particularly in relation to financial considerations, has further emphasized its role as a catalyst.

As researchers focused on issues pertaining to finance, policy and innovation, this study examining linkages within G20 contexts makes an important contribution towards supporting sustainable development goals. Upon reviewing the empirical findings, a few recommendations emerge for strengthening integrated progress in these spheres going forward. Examining the beneficial effects of sustainability on innovation, particularly in relation to financial considerations, has further emphasized its role as a catalyst. Policies within G20 nations that encouraged reductions in emissions, such as mandatory sustainability reporting and targets, had a significant impact in driving innovative solutions, according to this study's findings.

Its evident cooperation across sectors is vital yet complex dynamics remain in need of unpacking. Pilot collaborations targeting challenges within individual G20 nations may help untangle context-specific relationships. Lessons learned from collaborating on place-based sustainability transitions could then inform broader multi-stakeholder partnerships. Policymakers should pursue a comprehensive, multidimensional approach when crafting regulations. Rules should aim to promote customized and inclusive green financing systems through initiatives like expanding dedicated lending programs, innovation hubs supporting SMEs, and prudent market oversight.

Mainstreaming sustainability criteria within bank governance and lending practices may strengthen incentives for innovative solutions while boosting long-term financial performance long-term. Gradual implementation should balance risks with opportunities. Learning exchanges between pioneers and lagging G20 members could help surmount barriers. Businesses can gain competitive advantages by actively involving stakeholders to identify opportunities associated with sustainability. Cross-industry collaborations also enhance the exchange of new ideas. Overall, the findings point towards untapped potential if G20-scale thinking shifts towards integrated innovation development, finance networks, and strategic collaborations. With research insights, these economies can pioneer sustainable systems change through targeted policy experiments and multi-stakeholder partnerships.

Despite the limitations of this study, such as data and time period constraints, measurement challenges, and inability to fully address endogeneity, the findings provide valuable policy guidance for maximizing cooperation between sustainability and economic goals. The ongoing analysis, which focuses on specific G20 contexts, is advanced through collaboration between researchers and policymakers. This collaboration leads to practical actions that address shared real-world priorities. However, there is still room for improvement. Future research directions include conducting qualitative case studies within G20 nations to help disentangle complex issue dynamics. As more longitudinal data becomes available, expanding the scope and timeframes analyzed may reveal additional intricacies in the relationships over time. Alternative econometric techniques could also better address endogeneity and potential nonlinear influences. Incorporating industry-level or local data could expose conditionally distinct patterns. Surveys and interviews augmenting statistical analyses with qualitative inputs may further enhance understanding. Comparative analyses involving both G20 and non-G20 samples have the potential to shed light on whether sustainability-economy linkages vary by development level. Continuous collaborative efforts enhancing knowledgeable discussions between evidence and practice are important given the pressing need to expedite transformations within impactful G20 contexts.

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## Authors' contributions

DFH conducted all aspects of the study, including study design, data collection, analysis, and manuscript preparation. DFH also reviewed and approved the final manuscript.

## Availability of data and materials

Upon request, the data and materials will be made available.

## Disclosure statement

The author states that there are no competing interests to declare.

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## Tools statement

The author used STATA 17 and obtained a valid license for it.

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