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Digital Transformation, Green Finance, Carbon Footprint, and Green Innovation: Evidence from Developed and Developing Economies

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Abstract

This study examines how digital transformation, innovation culture, cultural capital, digital media literacy, and research and development (R&D) intensity influence carbon footprint reduction and green innovation in developed and developing economies. It also explores the mediating mechanism of media coverage intensity and green finance, and the moderating mechanism of environmental regulations. The study uses secondary panel data from 10 developed and 10 developing countries covering the period 2000–2024. Data were obtained from the World Development Indicators (WDI), OECD, and Eurostat databases and analysed using the two-step System-Generalised Method of Moments (System-GMM) estimator. The results show significant differences in developed and developing economies. Digital transformation and innovation culture have stronger positive effects on carbon footprint reduction and green innovation in developed economies than in developing economies because of differences in digital infrastructure, institutional quality, financial development, and dependence on fossil fuels. Likewise, in developed economies, cultural capital and R&D intensity have a more positive influence on carbon footprint reduction and green innovation than in the developing economies in which institutional and resource weaknesses limit the impact of these factors. Media coverage intensity and green finance serve as the important mediating variables and environmental regulations amplify the relationship between the explanatory variables and carbon footprint reduction and green innovation under different degrees of effects, with the former role being stronger in developed countries. Theoretically, the study combines the concepts of Institutional Theory with Resource Based View (RBV) to understand that knowledge of the role of strategic resource capability and institutional environment taken together on environmental performance in different economic conditions. From a methodological perspective, it presents comparative evidence based on a dynamic panel approach, and its results conclude with policy recommendations to signal the need for improving digital infrastructure, green finance, and institutional quality to drive the faster and more sustainable transitions, especially in developing economies.

Keywords: Digital transformation, carbon footprint reduction, green innovation, green finance, environmental regulations, innovation culture, digital media literacy.

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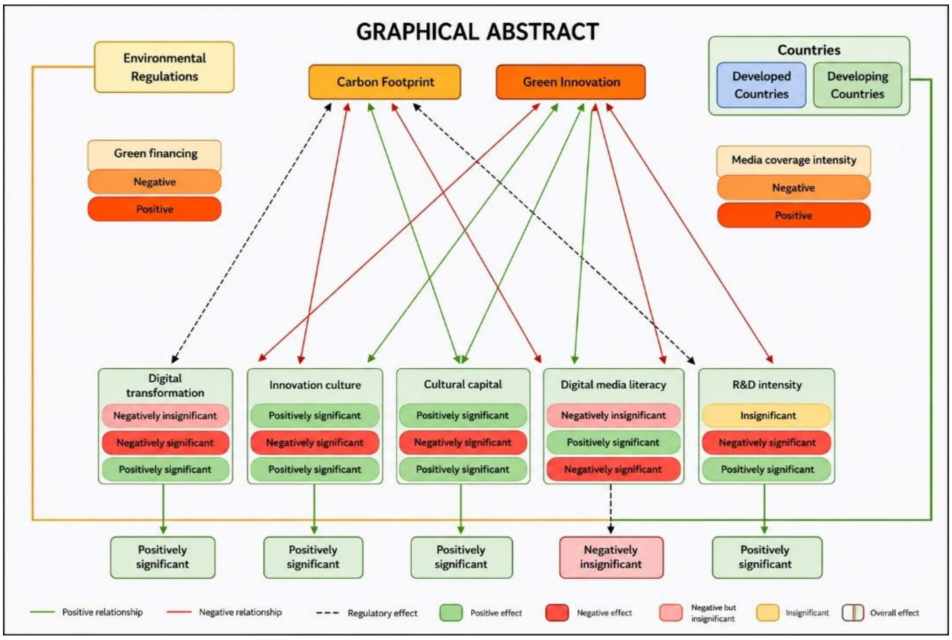
Graphical abstract



1. Introduction

The growing concern on climate change has resulted in the pressing need to develop evidence-based strategies to minimize carbon emissions and promote green innovation. Such environmental issues have exerted massive pressure on the developed and developing countries to deploy sustainable solutions (Rauniyar *et al.*, 2022). As the developed countries have already carried out much progress in combating climate changes by adopting digital transformation, green technological solutions and green production practices, the developing ones still have to encounter considerable costs because of budgetary constraints, institutional shortcomings, and the slower pace of digital technology and green technology adoption (Martínez-Peláez *et al.*, 2023).

The decrease of carbon footprint continues to be a high concern in the environmental management and climate change mitigation of the globe, and it is vital to know the factors behind it in order to develop effective sustainability measures (Sarfraz *et al.*, 2022). In developed countries, the utilization of both digital transformation and strong innovation culture, as well as explicitly large amounts of investments in R&D have helped to achieve substantial advancement in the field of carbon emission reduction and green innovations. As an example, the European Union promise to cut its carbon footprint in the period between 2010 and 2020 represents the efficiency of strict environmental regulations that are underpinned by financial and technological mechanisms. Nevertheless, the shift has not been as efficient in developing nations, as the industrialization, urbanization, and reliance on fossil fuels have led to the higher carbon emission (Sjachriatin *et al.*, 2023).

The role of green innovation in facilitating sustainability cannot be overemphasized, and it includes aspects such as taking up industrial practices, green energy solutions, and environmental technology (Zhu *et al.*, 2024). Green innovation has been widely adopted in developed economies with greater success due to the access to improved R&D infrastructure, public incentives, and private investment (Martínez-Peláez *et al.*, 2023). Conversely, developing economies are faced with the challenges of poor R&D investment, insufficient regulatory frameworks, and limited technological diffusion, which these aspects negatively affect the adoption of green innovations. The increasing difference between developed and developing countries in regard to the level of green innovation uptake demands specific policies and measures that allow a more equal shift towards achieving sustainable practices.

Digital transformation constitutes a catalyst for sustainable development and for advancing green innovations for more efficient utilization of energy and better optimization of utilization of resources through technologies, including artificial intelligence (AI), blockchain and big data (Clemente, 2023). In the developed world, the increase in the use of digital technologies has resulted in more effective emission reduction policies, higher energy efficiency, and more access to information that creates awareness of sustainability (Yin, 2023). On the other hand, developing nations cannot fully utilize digital technologies because they do not have well-developed digital infrastructures and digital media literacy is also lower. Although digital media literacy increases general awareness about sustainability concerns and leads to a more eco-friendly approach to the behavior in already developed economies, the effect is less significant in developing economies, where people do not have access to quality digital information.

Another important factor in green innovation adoption is cultural capital such as education, environment awareness, and social values (Zhu *et al.*, 2024). Cultural capital is higher in these countries, and society is more dedicated to sustainable production, and green policies are better sustained (Alpdemir *et al.*, 2024). Nevertheless, in developing nations, the absence of environmental education and institutional insufficient support hinder the universal utilization of green technologies. Likewise, the contribution of green finance, including green bonds and sustainable investments, has played a vital role in ensuring the shift to a low-carbon economy of developed countries. Developing countries, on the other hand, struggle heavily to access the green financing because of lack of financial means and poorly developed green financial policy.

While the body of literature on digital transformation, green finance and environmental sustainability has grown significantly, there exist some important gaps in theory and practice. Past research has investigated the impact of digital transformation on environmental performance in developed economies and developing economies separately, or for different types of relationships between digital transformation and environmental performance, but has not focused on the mechanisms linking these relationships across differing institutional environments (Zhao *et al.*, 2023). Recent works have also included the increasing significance of green finance for fostering low-carbon development and environmental sustainability, and the examinations have been either nonlinear relationships or country-specific considerations, but did not jointly investigate the implications of digital transformation, mediation, and institutional and environmental conditions in comparative cross-country analyses (Wang *et al.*, 2024). Moreover, the impact of media coverage intensity and green finance as mediators of the relationships between strategic resource capabilities and carbon footprint reduction and green innovation is not well substantiated, and the strength of these relationships is not well understood across various economic contexts, even in the presence of environmental regulations.

In response to these gaps, this study constructs a cross-sectional framework that combines the Institutional Theory with the Resource Based View (RBV) theory to analyze the relationship between digital transformation, innovative culture, cultural capital, digital media literacy and R&D intensity with the carbon footprint reduction and green innovation for developed & developing economies. The study has a few significant contributions to the literature. First, it builds on previous studies by exploring both direct and indirect as well as mediating and moderating constructs as all part of the same comparative analysis. Second, it establishes methodological evidence by analyzing 20 countries over the span of time 2000-2024, thus allowing for a systematic comparison of sustainability pathways in various developed and developing economies. Lastly, it provides context-related policy recommendations, showing how the institutional environment, digital infrastructure, green finance, and environmental rules affect environmental performance and sustainable transitions in various economic settings.

2. Literature Review

2.1. *Theoretical Framework*

This research is an amalgamation of Institutional Theory and Resource-Based View (RBV) to elucidate the distinct role of institutional conditions and strategic resource endowments on the phenomenon of sustainability between developed and developing economies. According to the version of Institutional Theory, regulations, governance capability and policy design will affect the implementation of environmentally friendly practices by imposing formal and informal institutional pressure (North, 1968). The country level adoption of good environmental regulation, supportive public policy, and institutional quality fosters digital transformation, green innovation, and carbon emission reduction, while institutional weaknesses impede sustainability transitions in many developing countries.

The Resource-Based View (RBV) has first been introduced at the level of the individual firm (Barney, 2001), but extended to macro-level includes, recently, national technological capabilities, innovation systems, human capital, research capacity, and digital infrastructure as strategic resources that increase environmental performance and sustainable competitiveness. Accordingly, countries that are more digital, stronger R&D nations, more innovative and have stronger access to green finance are expected to have better sustainability results.

Combining the Institutional Theory and the Resource-Based View (RBV) portrays a comprehensive explanation of sustainability transitions with the strategic capability in resource capabilities and institutional settings. In this context, digital transformation can be viewed as a strategic national capability aimed at bolstering technological competitiveness or an adaptive process in response to institutional pressures generated by environmental regulations, governance quality and sustainability policies. Carbon footprint reduction and green innovation are shaped by strategic resources, such as digital transformation, innovation culture, cultural capital, digital media literacy, and R&D intensity, and the degree to which these resources bring environmental benefits is determined by institutional conditions, including environmental regulations, green finance, and the intensity of media coverage. Therefore, the gaps in institutional quality, digital infrastructure, financial development, industrial structure and energy dependence account for the disparities between developed and developing economies in sustainability outcomes.

2.2. *Digital transformation and Carbon Footprint*

Digital transformation is becoming a major topic for sustainability transitions because technologies such as artificial intelligence (AI), Internet of Things (IoT), blockchain, and big data analytics are enhancing the efficiency of resource use, energy management, and the implementation of low-carbon production systems, among others (Jayathilaka *et al.*, 2024). As previously reported, the use of digital technologies has been found to reduce carbon emissions, through their beneficial impacts on operational efficiency and renewable energy integration (Clemente, 2023). But empirical results are still not consistent. In developed economies, high-quality digital infrastructure and environmental governance have contributed to environmental benefits, whereas these benefits have been compromised in developing economies due to a lack of effective environmental governance and advanced digital infrastructure and reliance on fossil fuels (Zaman *et al.*, 2024). In the context of Institutional Theory, favorable regulatory cultures unlock the potential for successful digital transformations, while the Resource-Based View offers a position on the effectiveness of converting into sustainable environmental outcomes based on a country's digital capability and technological resources (North, 1968). Although there is increasing evidence that digital transformation has environmental impacts, there has been little comparative research that considers the interaction of the intensity of media coverage and the role of green finance in transmitting the effects of digital transformation on carbon footprint reduction between countries with varying institutional quality and digital development levels. This unknown gap is the theoretical basis for the following hypothesis. This study thus fills a research gap by employing a comparative analysis of the cross-country perspective.

H1a: Digital transformation has a significant impact on carbon footprint reduction.

2.3. *Innovation Culture and Carbon Footprint*

Innovation culture, measured through ongoing investments in research, technological progress, and the generation of knowledge, is considered a key element in the sustainability of an environment. The findings of previous studies show that generally the reduction in carbon emissions is more effective in innovation-oriented economies by implementing cleaner technologies and by adopting environmentally friendly production processes (Alpdemir *et al.*, 2024). Innovation activities can generate short term energy consumption because it takes energy demands to conduct innovation R&D, industrial upgrading, and technology deployment, in the meantime, before its environmental benefits are realized (Sharma *et al.*, 2021). Although contrasting findings, these results indicate that the environmental dimension of the innovation culture is based on the quality of institutions, resources and technological advancement.

In line with the integrated Institutional Theory–RBV framework, environmental benefits of innovation culture are dependent on both strategic innovation capabilities and supportive institutional environment. Countries with better institutional quality, digital infrastructure, and financial development would benefit from the innovation investments in this manner to reduce carbon footprint, while countries with weak governance, industrial reliance on fossil fuels, but inadequate finance have limited opportunities. Although there is growing evidence on innovation and environmental performance, little comparative research has focused on how the effects of innovation culture on carbon footprint reduction are carried through by media coverage intensity in varying institutional contexts. This unfilled gap is a theoretical justification for the following hypothesis.

H2a: Innovation culture has a significant impact on carbon footprint reduction.

2.4. *Cultural Capital and Carbon Footprint*

Cultural capital is the awareness, education and pro-environmental social values in the environment, which is important for the promotion of sustainable behaviors and for supporting environmental policies (Zaman *et al.*, 2024). Prior research studies have indicated that societies with higher environmental awareness, can more easily adopt green technologies, encourage sustainable consumption patterns and facilitate carbon reduction efforts (Sharma *et al.*, 2021). However, cultural capital is different from country to country because values towards the environment are influenced by institution quality, form of education and public policy support. Developed economies tend to have higher levels of public awareness of the environment and public engagement in environmental actions, while developing economies still have environmental education and institutional capacity limitations.

In the integrated framework of the Institutional Theory–RBV, cultural capital would be a strategic capacity in the country whose environmental advantages would rely on the quality of institutions, the level of environmental governance, and public policies. Hence, in developed economies with better educational structures and institutional capacity, cultural capital can be converted more easily to a reduction in carbon footprint, whereas in less developed economies, cultural capital often comes with a host of constraints that stem from less developed institutions and lower environmental consciousness. But there is still little comparative evidence on whether media coverage intensity can reinforce this link under different economic contexts, so the theoretical foundations for the following hypothesis are provided.

H3a: Cultural capital has a significant impact on carbon footprint reduction.

2.5. *Digital Media Literacy and Carbon Footprint*

Digital media literacy is the competence of people and organizations that enable them to access, assess and use information from digital environments for informed decisions. In earlier research, positive relationships between digital literacy and, environmental awareness, responsible consumption and sustainable practice have been established (Suwandi, 2022). But the impact of digital media literacy on the environment is not universal, as the availability of misinformation, inequitable digital access, and institutional constraints can reduce the impact, especially in developing economies. These differences tend to be more striking in the developing economies, where digital capacity and digital infrastructure is relatively low when compared with the developed economies.

Drawing on the integrated institutional theory-RBV framework, digital media literacy is regarded as a strategic competence and the viability of the competence is contingent upon institutional support, digital infrastructure and accessibility of information (North, 1968; Barney, 2001). Consequently, this effect should be more pronounced in developed economies than in developing ones by helping reduce carbon footprints. While connections between digital literacy and sustainability have been explored more recently, there is little cross-country evidence that clarifies how and why the relationship between these constructs might be mediated by intensity of coverage in the media environment. This gap is the basis for the following hypothesis.

H4a: Digital media literacy has a significant impact on carbon footprint reduction.

2.6. *R&D intensity and Carbon Footprint*

R&D intensity, usually defined as research and development expenditure as a percentage to GDP, has been broadly accepted as being a significant indicator of technological innovation and low-carbon development (Ding *et al.*, 2022). The high-quality empirical studies show that more investment in R&D tends to stimulate the development of renewable energy technologies, cleaner production processes and carbon emission reduction (Wang *et al.*, 2021). R&D activities, however, could initially lead to a rise in carbon emissions, since R&D infrastructure and technological development consume a considerable amount of energy in the first place, before the benefits for the environment start to become visible. The mixed results suggest that the implementation of R&D is influenced by the financial resources, institutional quality, and supportive environmental policies. Overall, the intensity of R&D contribution is typically higher in developed economies due to their more developed innovation ecosystem, their advanced research institutions, and the available financial capacity.

In the integrated Institutional Theory–RBV framework, the intensity of R&D is a component of strategic national resources in which the environmental returns rely on institutional quality, financial development and regulatory supports. Thus, developed economies typically have stronger potential reducing the overall carbon footprint, while in developing economies; the benefits are often constrained by institutional or financial factors. Although evidence on R&D and environmental performance has been growing, limited comparative literature has investigated whether there is an intermediary role of green finance between these two variables in developed and developing countries. This unexplainable gap is the theoretical basis to support the following hypothesis.

H5a: There is a significant impact of R&D intensity on carbon footprint reduction.

2.7. *Digital Transformation and Green Innovation*

Digital transformation has emerged as a key driver of green innovation, supporting intelligent resource utilization and energy optimization, and providing environmentally friendly production processes (Li *et al.*, 2023). Previous research indicates that digital technologies generally enable eco-innovation through enhanced operational efficiency and help organizations develop eco-tech adoption. But digital transformation alone is not enough to ensure green innovation, unless it comes with proper institutional facilities, technologies and funding. The conflicting results suggest that the impact of digital transformation is not entirely the result of internal capacity building, but also relies on external regulatory systems.

In line with the integrated institutional theory–RBV framework, digital transformation described as a means of strengthening green innovation is a strategic resource capability as well as an adaptive response to institutional pressures, and depends on effective governance, financial systems and digital infrastructure (Cao & Gao, 2024; Lu *et al.*, 2025; Ran & Zhang, 2023). However, few comparative studies have analyzed the interaction between media coverage intensity and green finance and the relationship between digital transformation and green innovation between developed and developing economies. This gap is the basis which led to the following hypothesis.

H1b: Digital transformation has a significant impact on green innovation.

2.8. *Innovation Culture and Green Innovation*

Innovation culture is defined as a commitment of the organization and national level to permanent technological progress, research funding and knowledge generation, which makes a contribution to the green innovation and sustainability. Studies in this context have previously shown that innovation-driven economies tend to be more capable of developing environmentally friendly technologies and generating outstanding green innovation performance (Olojede *et al.*, 2024; Shi & Yang, 2024; Z. Zhang *et al.*, 2025). However, the effectiveness of the innovation culture varies from country to country as financial conditions; institutional performance and technological capability affect the commercialization of the green innovations. Developed economies generally have better innovation ecosystems while the innovation ecosystems in developing economies may face challenges because of limited finances and less institutional support.

Within the integrated Institutional Theory–RBV framework, innovation culture generates green innovation when supported by strong institutional quality, financial development, and effective innovation ecosystems. These supportive factors are available with greater frequency in developed nations than in developing nations (Muisyo & Qin, 2021). However, few comparative studies have explored how green finance allows innovations' culture to be translated into green innovation under various institutional conditions. The above research gap forms the theoretical basis for the following hypothesis.

H2b: Innovation culture has a significant impact on green innovation.

2.9. *Cultural Capital and Green Innovation*

Cultural capital, as evidenced by environmental awareness, education and pro-environmental social values has significant implications for green innovation and sustainable development (Rong & Yang, 2023). But the societies that have high environmental values are more inclined towards sustainable consumption, green technology employment, and implementing an environmentally friendly policy (Levidow *et al.*, 2021). The role of cultural capital in green innovation may be different in developed and developing countries, respectively, due to differences in education systems, environmental awareness, institutional quality, and access to green technology.

The institutional theory–RBV framework implies that culture can stimulate green innovation, provided that it has robust institutional quality, good environmental governance, and adequate financial capacity. The enabling conditions are very different across developed and developing economies. More specifically, few comparative studies investigated how the intensity of media coverage and green finance enhance this relationship in different financial conditions, supporting the ensuing hypothesis.

H3b: Cultural capital has a significant impact on green innovation.

2.10. *Digital Media Literacy and Green Innovation*

Digital media literacy is the ability of all persons, organizations and societies to access, assess and employ information in relation to the environment in digital media for sustainable decision making. Previous research indicated that digital literacy holds the potential to foster green innovation through raising environmental awareness, enhancing knowledge exchange, and encouraging the use of energy-efficient technologies (Liu & Song, 2023). However, misinformation and unequal access to the digital field, as well as weak institutional backing, particularly in developing economies, can weaken the impact on green innovation. Such obstacles tend to be more significant in less developed economies due to poor digital infrastructure, lack of equal access to the internet, and less support of digital transformation institutions (Olojede *et al.*, 2024; Shi & Yang, 2024; Z. Zhang *et al.*, 2025).

In the integrated framework of Institutional Theory–RBV, digital media literacy facilitates the access to greener knowledge and enhances the possibility of informed decision-making, thus promoting the process of green innovation, however, contingent to the quality of the institutions and digital infrastructure (Ding *et al.*, 2022). Although more studies have focused on the connection between digital literacy and green innovation, there is still a lack of comparative evidence that looks at the involvement of media coverage intensity in this connection between digital literacy and green innovation in developing and developed economies. In consequence, this unsolved gap is the theoretical basis for the following hypothesis.

H4b: Digital media literacy has a significant impact on green innovation.

2.11. *R&D Intensity and Green Innovation*

R&D intensity is an important determinant of green innovation as investment in R&D facilitates the generation of renewable energy technologies, cleaner production methods and low-carbon solutions (Cao & Gao, 2024; Lu *et al.*, 2025; Ran & Zhang, 2023). Previous research mainly indicates that a greater R&D capability is associated with greater economies' potential to create green patents, environmental technologies and sustainable industrial upgrading (Muisyo & Qin, 2021). The impact of R&D intensity is different in other countries: developed countries have generally better research capabilities (including research institutions, financial support etc.), and developing countries may have limitations in funding, technology diffusion and research support.

Within the framework of integrated Institutional Theory – RBV, R&D intensity is a strategic capability which is influenced by the institutional conditions, the financial development, and the innovation ecosystem for green innovation (Lin *et al.*, 2021). These conditions tend to be more pronounced in more developed economies than in less-developed economies. In contrast, few comparative studies examine whether green finance serves as the mediating variable between the variables under study in different institutional contexts. The above research gap is the basis for the following hypothesis.

H5b: There is a significant impact of R&D intensity on green innovation.

2.12. *The mediating effect of Media coverage intensity*

Media coverage intensity is expressed by the amount, frequency and visibility of environmental and sustainability-related information coverage in traditional and electronic media that affects the resources, pressure of the institutions and the behavior of the institutions in terms of environmental behavior of the organizations (Huang *et al.*, 2021). Research has indicated that robust media coverage may have a positive effect on governments and companies' greater activity in addressing environmental issues through greater transparency, pressure on citizens, and policy accountability (Jayathilaka *et al.*, 2024). The mediating effect of media coverage could be different between developed and developing economies given that there are differences in public engagement, environmental journalism, digital accessibility, and media freedom. According to Institutional Theory, media plays roles in putting pressure on normative and societal sustainability, and the Resource-Based View presents the environment information communication capabilities as resources that can help achieve green innovation and lower carbon emissions (Liu & Song, 2023). Media coverage intensity is not only a means of communication, but also a mediating process, which boosts public awareness, enhances stakeholder pressure, enhances the transparency of relevant information and spurs governments and organisations to convert digital capabilities and innovations into carbon footprint reduction and green innovations. Attracting more media attention can drive institutional pressures, inform investors, and help spread sustainable practices. These mechanisms are likely to be more robust in well-developed economies, where the level of media freedom and the digital accessibility of information and services, as well as the transparency of institutions, tend to be higher. Therefore, media coverage intensity is theorized to mediate the relationships between the explanatory variables and environmental outcomes.

H6: Media coverage intensity has a significant mediating role in innovation culture, digital transformation, digital media literacy, cultural capital, R&D intensity, carbon footprint reduction and green innovation.

2.13. *The mediating effect of green financing*

Green finance has evolved into a crucial financial mechanism to support renewable energy, low-carbon technologies, green infrastructure, and environmental innovation (Valencia & Calabuig-Tormo, 2023). Previous research indicates that green finance can facilitate the process of translating technological capabilities and innovation resources into tangible sustainability outcomes by lowering the financial hurdles associated with uptake of clean technology (Ye & Dela, 2023). Nevertheless, the distribution of green finance access is not even between developed and developing economies. Developed countries tend to have more advanced green bond markets, robust financial institutions and regulatory clarity surrounding sustainability regulations while developing countries experience lags in access to climate finance, investment risk, and funding limitations in the regulatory framework (Huang *et al.*, 2021). In the RBV context, financial resources can be viewed as key sustainability transition strategic assets, and in the Institutional Theory, regulatory regimes and financial governance are interwoven and can influence a company's green investment behavior (North, 1968). The intermediation effect of green finance lies in its ability to alleviate the financial constraints of clean technologies and sustainable finances and combine technological capabilities or innovation inputs with environmental effects and natural resources. Strong digital capabilities and innovative resources are positively correlated with countries attracting green financial resources that eventually enable investments in renewable energy, cleaner production technologies and environmentally friendly projects. This mediation is likely to be more efficient in advanced economies due to more advanced financial markets and institutional contexts. Therefore, this research introduces Green Finance as a mediating variable in this study that connects the explanatory variable to the reduction of the carbon footprint and green innovation.

H7: Green financing has a significant mediating role in innovation culture, digital transformation, digital media literacy, cultural capital, R&D intensity, carbon footprint reduction and green innovation.

2.14. *The moderating effect of Environmental Regulations*

Environmental regulations are one of the most important institutional measures to foster the reduction of the carbon footprint and the adoption of green innovation. Regulations have differing pathways to influence sustainability through command and control instruments (emission standards, pollution control instruments), market based incentives (green subsidies, carbon pricing, emissions trading schemes), and information disclosure instruments (environmental reporting, sustainability disclosure requirements) (Li *et al.*, 2024). These regulatory mechanisms can be effective in different countries depending on the institutional quality, governance ability, financial development, industrial structure, and energy dependence of each country. Developed economies tend to have more comprehensive and well-enforced regulatory regimes than do developing economies, which may have institutional or enforcement limitations. In this integrated framework of institutional theory-RBV, green institutions in the form of environmental regulations act as external institutional pressures to enhance the capacity of strategic national resources such as digital transformation, innovation culture, cultural capital, digital media literacy, and R&D intensity in order to secure carbon footprint reduction and green innovation (North, 1968; Barney, 2001). Thus, the aim of this study is to analyses the moderating effect of environmental regulations on the relationship between digital transformation, innovation culture, cultural capital, digital media literacy, R&D intensity and sustainability outcomes.

H8: Environmental regulations have a significant moderating role in innovation culture, digital transformation, digital media literacy, cultural capital, R&D intensity, and carbon footprint reduction and green innovation.

3. Research Methodology

3.1. *Research Design and Approach*

This study employed a quantitative research design and was analyzed with panel data analysis for the purposes of examining the relationships between digital transformation, innovation culture, cultural capital, digital media literacy, R&D intensity, green finance, environmental regulations, carbon footprint and green innovation in developed and developing economies. The authors made a panel dataset constituted of 20 countries, 10 developed and 10 developing, for the period 2000–2024 in order to capture the longitudinally varying sustainability outcomes and make cross-country comparisons.

The countries selected were based on their economic classification and technological development, environmental policy direction, and availability of consistent data over the entire study period. The comparative design allowed the study to compare sustainability outcomes under the different economic circumstances and assess the influence of differences in institutional environments and technological capabilities.

3.2. *Sample Selection*

The sample comprised ten developed economies (namely, Germany, the United States, the United Kingdom, Sweden, Japan, South Korea, France, Canada, the Netherlands and Australia) and ten developing economies (China, India, Brazil, South Africa, Mexico, Indonesia, Nigeria, Vietnam, Kenya and Egypt). The countries were chosen to demonstrate a range of digital transformation levels, innovation capacity, environmental regulation and sustainability performance and because robust sets of data have been available for the study period in each country.

The final data set was a country-year balanced panel for meaningful comparisons between developed economies and developing economies.

3.3. *Data Collection and Sources*

Secondary data from the internationally recognized databases, namely (World Development Indicators) WDI, OECD and Eurostat, was used for the study. The data were gathered between 2000 and 2024, offering a comprehensive long-term view of sustainability transitions, technological advancements, and environmental impact.

To make variables comparable across countries and over time, the variables were obtained from the selected databases, coded using internationally comparable indicators. For some sample countries, the lack of direct measures at the macro level of the theoretical constructs necessitated the use of internationally recognised proxy indicators in the 2000–2024 period. The proxies were selected because they offer cross-country consistency, are readily applied at the macro level in sustainability studies, and allow for the analysis of panels in a comparable manner. The operationalisation, theoretical justification, and limitations of each proxy variable are presented below.

Table 1. Variables and their Measurements.

Variables	Operational Proxy Indicator	Unit of Measurement	Data Source
Carbon Footprint (CF)	Greenhouse gas emissions	*(actual WDI unit)*	WDI
Green Innovation (GI)	Renewable energy consumption	% of total final energy consumption	WDI
Digital Transformation (DT)	Businesses employing ICT specialists	Percentage of enterprises	OECD
Innovation Culture (IC)	Research and development expenditure	% of GDP	WDI
Cultural Capital (CC)	Cultural employment	Percentage of total employment	Eurostat
Digital Media Literacy (DML)	Persons regularly using computers at work	Percentage of employment	OECD
R&D Intensity (RDE)	Researchers in R&D	Per million people	WDI
Media Coverage Intensity (MCI)	Households with Internet access at home	Percentage of households with internet access	OECD
Green Financing (GF)	Investment in energy with private participation	Current US$	WDI
Environmental Regulations (ER)	Environmental sustainability rating	Scale (1 = low, 6 = high)	WDI

The constructs of green innovation, cultural capital, digital media literacy, media coverage intensity and environmental regulations are not consistently available for both developed and underdeveloped countries in the period 2000–2024, and are therefore operationalized as internationally recognized proxy indicators. The selected proxies ensure consistency and comparability across countries and over time. They may not be exhaustive enough to represent each element of the underlying constructs, but are good indicators at the macro-level for panel analysis across countries.

Green Innovation (GI) is operationalised using renewable energy consumption (% of total final energy consumption). While renewable energy use is not directly linked to measures of innovation output like environmental technologies or green patents, it does represent uptake and diffusion at a national scale. Renewable energy is the method used to access the level of green innovation across countries, given the absence of internationally comparable measures of green innovation for most countries for the entire study period, and is a widely-used macro level proxy for sustainability across countries. However, using this proxy to measure green technological adoption does not measure the adoption of green technologies, but rather their results, an acknowledged limitation of the study.

Digital Transformation (DT) is measured by the percentage of businesses employing ICT specialists. This indicator is not comprehensive of all digital transformation aspects, including digital governance, AI adoption, or innovation in business models, but it does capture the level of specialisation of enterprises' digital capabilities needed to facilitate digitalisation of their organisations. Macro-level, availability of ICT specialist is considered an important determinant of digital readiness and technological capability. Because data from this proxy is uniformly available and comparable across sample countries over the course of the study period, it allowed for reliable comparative analysis. It is a representation of digital capability, however, not necessarily the full multidimensional idea of digital transformation.

Cultural employment represents a macro indicator of national investment in creativity and education, as well as in the production of knowledge and innovations, which help to build environmental awareness and capacity for innovation. This is not a complete reflection of cultural capital, but it is the best available measure for comparison over countries and time.

The concept of Digital Media Literacy (DML) is operationalized by measured the percentage for persons who use a computer on a regular basis for work. While the indicator does not directly measure digital media literacy, it indicates national digital capability and frequent usage of digital technologies. It has been widely available in various countries around the world, which makes it a good macro-level indicator for comparative panel analysis and admits that it cannot measure everything in terms of digital media literacy.

Household internet access is used as a proxy for Media Coverage Intensity (MCI) as increases in internet usage will mean greater public exposure to online news, digital media platforms and environmental information. While it is not a direct measure of environmental media coverage, it serves as one of the more reliable macro level indicators of the reach of sustainability related information between countries. These restrictions should be taken into account when interpreting findings.

Environmental Regulations (ER) are operationalised using the Environmental Sustainability Rating reported by the World Development Indicators (WDI). The indicator does not distinguish between command-and-control regulations, market-based instruments and information disclosure mechanisms, but it is comprehensive and consistently available across all sample countries for overall environmental governance and regulatory quality. Therefore, it is seen as a proper macro level proxy, and the fact that various regulatory instruments could have different impact pathways.

3.4. *Data Analysis Technique*

Data were analysed using STATA. A descriptive statistics have been calculated and briefly analysed to observe the range, mean, standard deviation, minimum and maximum of each variable. The pairwise correlation analysis was done to examine the degree of association between the variables and to look for possible multicollinearity.

Panel diagnostic tests were performed prior to the estimation of the empirical models. The slope heterogeneity was tested with (Hashem Pesaran & Yamagata, 2008), and Cross-sectional dependence was tested with Pesaran's Cross sectional Dependence (CD) test. The diagnostic tests were used to infer features of the panel data and the appropriateness of the estimation method.

The empirical analysis was carried out in a structured manner. To examine the nature of the panel data and identify the most relevant estimation approach for the empirical analysis, descriptive statistics, correlation analysis, tests of slope heterogeneity, and cross-sectional dependence tests were first performed. The two-step System-Generalised Method of Moments (System-GMM) estimator was then used to estimate the direct, mediating, and moderating relationships (Saprullah *et al.*, 2023; Tariq, 2025). The panel is comprised of 20 countries; however, the study incorporates lagged dependent variables and addresses the potential endogeneity from reverse causality, omitted variables, and simultaneity, making System-GMM appropriate. The instrument proliferation was achieved by combining the instrument matrix and decreasing lag depth, and the validity of the model was validated by Hansen, Difference-in-Hansen, Sargan, and Arellano–Bond AR(1) and AR(2) diagnostic tests. Robustness was additionally checked by means of alternative estimators to ensure consistency of results.

3.4.1. Estimation, diagnostics and robustness analysis

The dynamic panel models were estimated using the two steps System-GMM estimation, the finite sample correction was used to improve the efficiency of the estimated standard errors (Hassan *et al.*, 2024). Based on recommendations given by (Yitayaw *et al.*, 2023), the instrument matrix was collapsed, the lag depth was limited and the number of instruments administered is kept to less than the cross-sectional units used.

A single diagnostic framework was used to evaluate model validity. The Arellano-Bond AR(1) test and the AR(2) test were conducted to test for serial correlation, the Hansen, Sargan, and Difference-in-Hansen tests to test the validity of instruments, and the instrument count to test for instrument proliferation. These diagnostics together found that the chosen instruments were appropriate and the final estimation with the System-GMM approach was robust.

The results were robustly tested according to alternative estimation methods, such as Fixed Effects models with Driscoll-Kraay standard errors and the Augmented Mean Group (AMG) estimator. The robustness provided by the consistency of the results obtained from using alternative estimators offers further confidence that the relationships reported may not be sensitive to the estimation method or model specification.

3.5. *Model Specification*

3.5.1. Direct Effects Equations:

3.5.1.1 Carbon Footprint (CF) Equation:

$$\boldsymbol{CF_{it}} = \boldsymbol{a}_0 + \boldsymbol{a}_1\boldsymbol{CF_{it-1}} + \boldsymbol{\beta}_1\boldsymbol{DT_{it}} + \boldsymbol{\beta}_2\boldsymbol{IC_{it}} + \boldsymbol{\beta}_3\boldsymbol{CC_{it}} + \boldsymbol{\beta}_4\boldsymbol{DML_{it}} + \boldsymbol{\beta}_5\boldsymbol{RDE_{it}} + \boldsymbol{\mu_i} + \boldsymbol{\varepsilon_{it}}$$

Where:

- CFit: Carbon Footprint for country i at year t
- CFit−1: Lagged Carbon Footprint (captures dynamic effects)
- DTit: Digital Transformation
- ICit: Innovation Culture
- CCit: Cultural Capital
- DMLit: Digital Media Literacy
- RDEitt: R&D Intensity
- μi: Unobserved individual effects
- ϵit: Error term

3.5.1.2 Green Innovation (GI) Equation:

$$\boldsymbol{GI_{it}} = \boldsymbol{\theta}_0 + \boldsymbol{\theta}_1\boldsymbol{GI_{it-1}} + \boldsymbol{\gamma}_1\boldsymbol{DT_{it}} + \boldsymbol{\gamma}_2\boldsymbol{IC_{it}} + \boldsymbol{\gamma}_3\boldsymbol{CC_{it}} + \boldsymbol{\gamma}_4\boldsymbol{DML_{it}} + \boldsymbol{\gamma}_5\boldsymbol{RDE_{it}} + \boldsymbol{\delta_i} + \varsigma_{it}$$

Where:

- GIit: Green Innovation for country i at year t
- GIit−1: Lagged Green Innovation
- Other variables are as defined above
- δi: Unobserved individual effects
- εit: Error term

3.5.2. Mediating Effects of Media Coverage Intensity (MCI) and Green Financing (GF):

3.5.2.1 Media Coverage Intensity (MCI) Equation

$$\boldsymbol{MCI_{it}} = \boldsymbol{\sigma}_0 + \boldsymbol{\sigma}_1\boldsymbol{DT_{it}} + \boldsymbol{\sigma}_2\boldsymbol{IC_{it}} + \boldsymbol{\sigma}_3\boldsymbol{CC_{it}} + \boldsymbol{\sigma}_4\boldsymbol{DML_{it}} + \boldsymbol{\sigma}_5\boldsymbol{RDE_{it}} + \boldsymbol{\psi_i} + \boldsymbol{\eta_{it}}$$

Where:

- MCIit: Media Coverage Intensity for country iii at year ttt
- ψi: Unobserved individual effects
- ηit: Error term

3.5.2.2 Green Financing *(GF) Equation:*

$$GF_{it} = \vartheta_0 + \vartheta_1 DT_{it} + \vartheta_2 IC_{it} + \vartheta_3 CC_{it} + \vartheta_4 DML_{it} + \vartheta_5 RDE_{it} + \omega_i + \zeta_{it}$$

Where:

- GFit: Green Financing for firm iii at time ttt
- ωi: Unobserved individual effects
- ζit: Error term

3.5.3. Carbon Footprint with Mediators (MCI and GF)

$$CF_{it} = a_0 + a_1 CF_{it-1} + \beta_1 DT_{it} + \beta_2 IC_{it} + \beta_3 CC_{it} + \beta_4 DML_{it} + \beta_5 RDE_{it} + \sigma MCI_{it} + \vartheta GF_{it} + \mu_i + \varepsilon_{it}$$

3.5.4. Green Innovation with Mediators (MCI and GF):

$$GI_{it} = \theta_0 + \theta_1 GI_{it-1} + \gamma_1 DT_{it} + \gamma_2 IC_{it} + \gamma_3 CC_{it} + \gamma_4 DML_{it} + \gamma_5 RDE_{it} + \eta MCI_{it} + \phi GF_{it} + \delta_i + \varsigma_{it}$$

In both equations, the coefficients of MCIit and GFit capture the mediating effects.

3.5.5. Moderating Effect of Environmental Regulations (ER):

Environmental Regulations (ERit) are modeled as a moderating variable by introducing interaction terms:

3.5.5.1 Carbon Footprint with Moderator (ER):

$$CF_{it} = a_0 + a_1 CF_{it-1} + \sum_{j=1}^{5} \beta_j X_{it} + \sigma MCI_{it} + \vartheta GF_{it} + \theta ER_{it} \times X_{it} + \mu_i + \varepsilon_{it}$$

3.5.5.2 Green Innovation with Moderator (ER):

$$GI_{it} = \theta_0 + \theta_1 GF_{it-1} + \sum_{j=1}^{5} \lambda_j X_{it} + \eta MCI_{it} + \phi GF_{it} + \kappa ER_{it} \times X_{it} + \delta_i + \varsigma_{it}$$

Where:

- Xit represents the set of independent variables: DTit,ICit,CCit,DMLit,RDEit
- ERit × Xit represents the interaction terms to measure the moderating effect of Environmental Regulations

3.6. *Flow Chart of Methodology*

The methodological approach used in this research is shown here in **Figure 1**. The figure shows the overall research process, consisting of research design, data collection, variables operationalization, empirical estimation and interpretation of results.

3.7. *Conceptual Framework*

The conceptual framework of this study is shown in **Figure 2**, which depicts the potential relationships between the independent variables, mediating variables and the moderating variable, and sustainability outcomes.

4. Data Analysis

The structure of the empirical analysis is clearly defined. Descriptive statistics and pairwise correlations are presented first to give a summary of the variables' characteristics. Second, diagnostic tests are conducted across the panel to test for cross-sectional dependence, slate vs. slope heterogeneity and model validity. Third, the two-step System-GMM estimator is used to estimate the direct, mediating, and moderating relationships. Finally, robustness analyses are performed to ensure the consistency of the results.

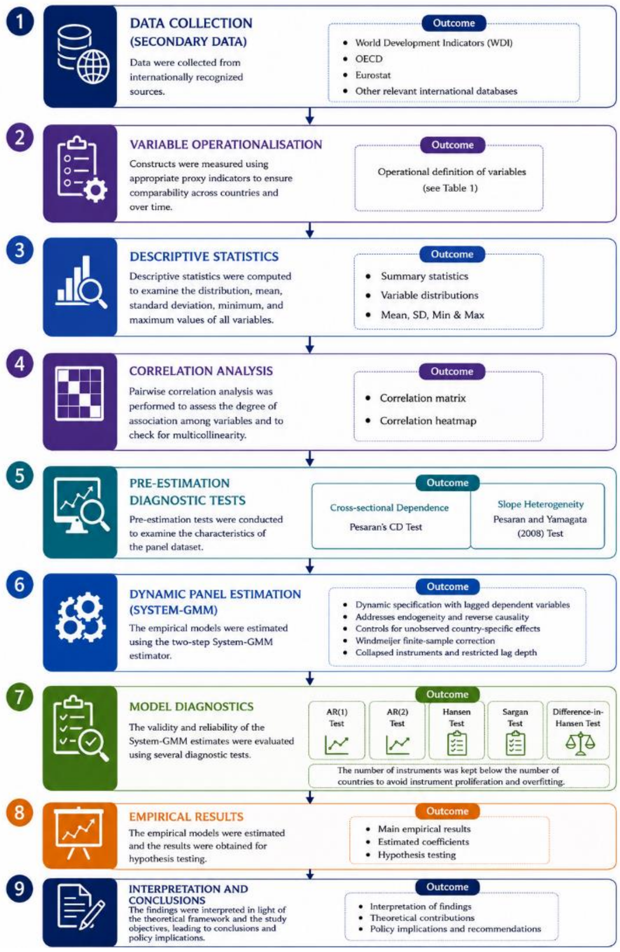


Figure 1. Flowchart of methodology

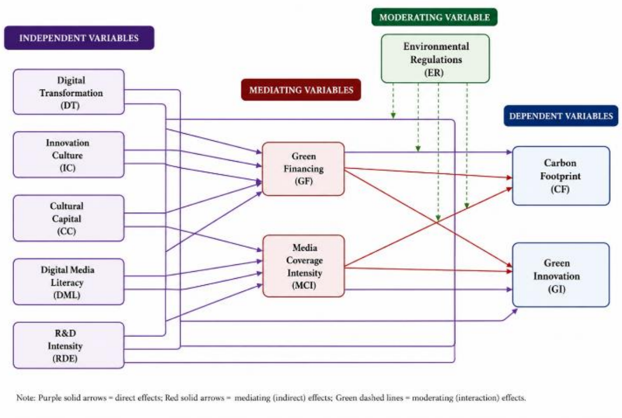


Figure 2. Conceptual Framework

4.1. *Descriptive Statistics*

Table 2 presents the data of 500 entities though there are 499 entities recorded in Digital Transformation (DT) and Media Coverage Intensity (MCI) in **Table 2**. The mean greenhouse gas emission in terms of Carbon Footprint (CF) is 2.791 and the standard deviation is 0.588 with a moderate level of emissions and very high differences between 1.024 and 4.16. The mean that is captured by Green Innovation (GI) is 1.162 and standard deviation of 0.472 which shows that there are significant differences between entities in the consumption of renewable energy. It depicts some negative values, whereby some organizations have low values of using renewable energy where others have high values of up to 1.945, which show greater usage of green energy. Digital Transformation (DT) has a mean of 1.32 and very low standard deviation (SD = 0.097), meaning that most companies have the same levels of digital adoption. Innovation Culture (IC) has an average of 0.047, which is accompanied by a huge standard deviation (0.443) indicating immense differences in the amount spent on R&D and the range of expenditure is between -2.493 and 0.693. The highest percentage of employment is made up of Cultural Capital (CC) 63.1% and SD 0.058 and employment patterns are similar across entities. Digital Media Literacy (DML) has a mean of 1.76 with a slight deviation (SD = 0.125), which means that the majorities of entities are at high levels of digital literacy. Finally, the Media Coverage Intensity (MCI) means 180.1 with standard deviation of 0.226 indicating that there are disparities in internet access rates among entities even though the overall rate of connectivity is high. Descriptive statistics at the country level are provided in detail in Appendix A, and trend plots of various main variables are included in Appendix B, together with a description of the changes in these variables on a developed versus developing country basis.

Table 2. Descriptive Statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
CF	500	2.791	0.588	1.024	4.16
GI	500	1.162	0.472	-0.155	1.945
DT	499	1.32	0.097	1.083	1.868
IC	500	0.047	0.443	-2.493	0.693
CC	500	0.631	0.058	0.398	0.74
DML	500	1.76	0.125	0.531	1.901
RDE	500	2.999	0.682	1.358	4.656
MCI	499	1.801	0.226	0.004	2
GF	500	8.841	0.776	6.778	10.473
ER	500	.561	0.057	.301	0.602

Table 3. Pairwise correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) CF	1.000									
(2) GI	-0.122	1.000								
(3) DT	-0.010	0.137	1.000							
(4) IC	0.052	-0.448	-0.062	1.000						
(5) CC	-0.341	0.101	-0.029	-0.142	1.000					
(6) DML	-0.081	0.020	0.028	0.123	0.109	1.000				
(7) RDE	-0.097	-0.506	-0.068	0.784	-0.160	0.163	1.000			
(8) MCI	-0.136	-0.165	0.313	0.367	0.074	0.129	0.369	1.000		
(9) GF	0.301	-0.074	-0.013	0.109	-0.039	-0.009	0.099	0.016	1.000	
(10) ER	0.062	-0.193	0.205	0.442	-0.177	0.001	0.449	0.389	0.277	1.000

Table 4. Cross Dependency Test

Pesaran's test of cross-sectional independence = −0.817, Pr = 0.4139
Friedman's test of cross sectional independence = 17.589, Pr = 0.5501

4.2. *Pairwise correlations*

Figure 3. Correlation heatmap of the study variables

Figure 3 presents the correlation heatmap and **Table 4** shows that the results of the pairwise correlation indicate that there is both a positive and negative correlation between the variables in the study. The relationship between Green Innovation (GI) and Carbon Footprint (CF) is weakly negative (-0.122), and therefore, the more people use renewable energy, the less greenhouse gas they emit. Cultural Capital (CC) and CF are also negative correlated (-0.341) meaning that cultural employment is higher, the less the emission. On the other hand, the moderate positive correlation between Green Finance (GF) and CF (0.301) suggests that the countries with higher investment levels are likely to have higher emissions during the study period. But this correlation should not be interpreted as causality since Pearson's correlations are simply associations. The negative correlations between GI and IC (-0.448) and between GI and RDE (-0.506) suggest that higher research activity does not necessarily translate into immediate improvements in renewable energy adoption, possibly reflecting the time required for innovation investments to generate environmental outcomes. Digital Transformation (DT) is positively associated with Media Coverage Intensity (MCI) (0.313) indicating that increasing the internet penetration increases ICT adoption. There is a high positive relationship between Innovation Culture (IC) and RDE (0.784), which indicates that research intensity is extremely dependent on the number of researchers. Environmental Regulations (ER) have moderate positive correlations with IC (0.442) and RDE (0.449) indicating the innovation development due to policies.

Table 5. Heterogeneity Test

Testing for slope heterogeneity (Pesaran, Yamagata. 2008. Journal of Econometrics) H0: slope coefficients are homogenous	
Delta	p-value
2.763	0.010
Adj.2.186	0.023
Variables partialled out: constant	

Table 6. Sargan test of overidentifying restrictions

H0: overidentifying restrictions are valid
chi2(176) = 646.5433
Prob > chi2 = 0.0000

Table 7. System-GMM Post-Estimation Diagnostic Results

Diagnostic Test	Result	Interpretation
AR(1)	Significant	Expected first-order serial correlation
AR(2)	Not significant	No second-order serial correlation
Hansen Test	Acceptable	Instruments are valid
Difference-in-Hansen	Acceptable	Instrument subsets are valid
Sargan Test	Reported	Supplementary only
Instrument Count	<20	Instrument proliferation avoided

4.3. *Cross Dependency Test*

The cross-sectional dependency tests in **Table 4** reveal that the variables in the dataset show no noteworthy indication of coexistence dependence. The results from Pesaran's test demonstrate a statistic of -0.817 at a p-value level of 0.4139 that exceeds 0.05, indicating no need to reject cross-sectional independence. Friedman's test generated statistical results of 17.589 with a p-value at 0.5501 to demonstrate that cross-sectional dependence is insignificant within the dataset.

4.4. *Heterogeneity Test*

The heterogeneity test developed by Pesaran and Yamagata in **Table 5** reveals the rejection of the hypothesis for slope coefficient homogeneity across the sample. Results show that the delta statistic equals 2.763 and achieved a p-value of 0.010 and a detected adjusted delta value of 2.186 with a p-value of 0.023. The significance thresholds below indicate that slope coefficient heterogeneity exists, demonstrating that the variable relationships vary throughout the sample data set.

4.5. *Sargan test of overidentifying restrictions*

System-GMM gave negative results for the Sargan test, suggesting there was some instrument misspecification. The model was then re-estimated by collapsing the instrument matrix, imposing restriction on lag depths, and decreasing the number of endogenous instruments. The revised specification was found to satisfy the Hansen, Difference-in-Hansen, AR(1) and AR(2) diagnostic tests, and thus instrument validity and model reliability are demonstrated. The final diagnostic results have been reported in the following **Table 6**.

The post estimation diagnostic results for the final two-step System-GMM model are summarized in **Table 7**. The significant AR(1) and insignificant AR(2) tests indicate that no second order serial correlation existed, and Hansen and Difference-in-Hansen tests indicate the instrument's validity. In addition, the number of instruments did not exceed the number of cross-sectional units, signifying successful control over proliferation of instruments, and the final model being statistically sound.

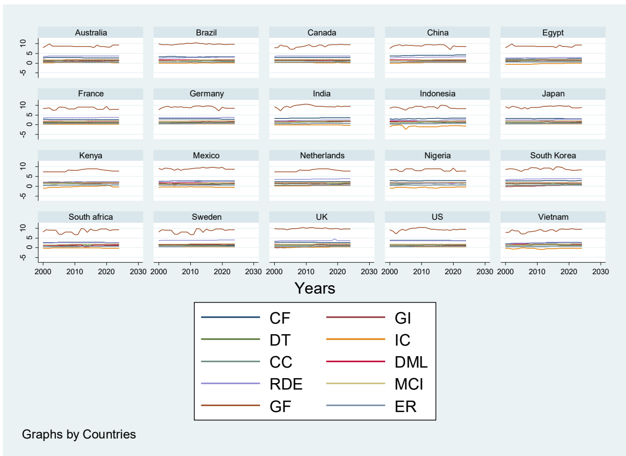


Figure 4. Variables by countries

The graph in **Figure 4** displays various time-series line charts to illustrate how multiple countries have evolved from 2000 to about 2030. Every subplot within the chart represents a nation that shows changes in multiple variables across different periods. The bottom image displays a legend that assigns specific colours for CF, DT, CC, RDE, GF, GI, IC, DML, MCI, and ER variables. These variables represent economic, business, and financial factors and technological measures across nations. The visualization shows minor fluctuations across variables, but significant changes tend to happen exclusively in selected countries.

Statistically, the DT variable shows a weak connection to the outcome in **Figure 5** and an insignificant result supported by its low t-value. The dependent variable demonstrates a positive relationship with IC because independent variable growth increases the dependent variable value. CC demonstrates a powerful negative link between its values and dependent variable variations. According to the plot, RDE generates a significant negative relationship with the dependent variable even though DML demonstrates an insignificant relationship. Some variables show heteroscedasticity, while others exhibit influential points affecting the model's efficiency.

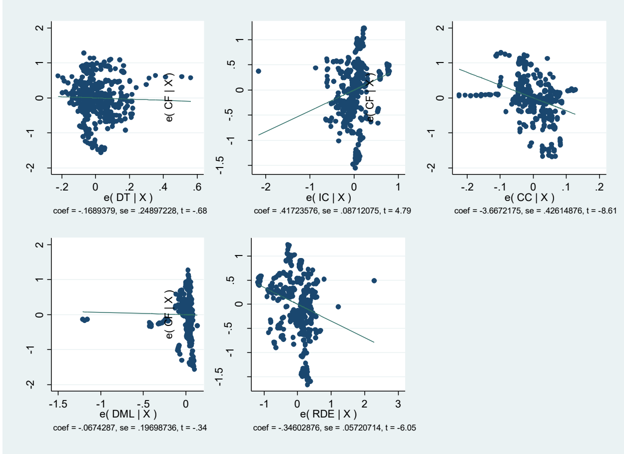


Figure 5. Added variables plot

Table 8. Westerlund Cointegration test

	Number of panels = 20 Avg. number of periods = 21.571 Ho: No cointegration Ha: All panels are cointegrated	
	Statistics	**P value**
Variance ratio	0.2971	0.5082

Table 9. Dynamic Panel Model Results.

VARIABLES	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
	CF	**MCI**	**GF**	**ER**	**CF**
DT	0.0346	0.486***	0.678**	0.252***	-0.0538**
	(0.0217)	(0.0455)	(0.333)	(0.0156)	(0.0225)
IC	-0.0294**	0.101***	-1.041***	0.0114	-0.0384***
	(0.0134)	(0.0306)	(0.264)	(0.0106)	(0.0128)
CC	-0.720***	-0.419***	1.975	-0.323***	-0.573***
	(0.0783)	(0.148)	(1.206)	(0.0453)	(0.0762)
DML	-0.0904***	0.104**	0.242	0.0527*	-0.101***
	(0.0240)	(0.0518)	(0.423)	(0.0305)	(0.0229)
RDE	0.108***	0.461***	0.972***	0.145***	0.0238
	(0.0134)	(0.0289)	(0.225)	(0.00962)	(0.0153)
ER					0.529***
					(0.0531)
Constant	3.037***	-0.149	3.411***	-0.0965	3.037***
	(0.0790)	(0.156)	(1.194)	(0.0668)	(0.0755)
Observations	499	498	499	499	499
Number of countries01	20	20	20	20	20

Standard errors in parentheses
**** p<0.01, ** p<0.05, * p<0.1*

4.6. *Westerlund Cointegration test*

A panel cointegration variance ratio test in **Table 8** analyzed twenty panels containing 21.571 periods on average. The null hypothesis establishes the nonexistence of cointegration between panels, but the alternative hypothesis confirms that all panels demonstrate cointegration. The test provided a variance ratio of 0.2971; the obtained p-value amounted to 0.5082. A p-value of 0.5082 exceeding standard levels at 0.05 or 0.10 prevents the rejection of the null hypothesis. A p-value of 0.5082 from this test indicates no statistical evidence of a long-run relationship between panel variables because they exist independently throughout time.

4.7. *Dynamic Panel Model Results*

Initial GMM runs failed the Sargan test (p<0.001), indicating instrument misspecification as indicated in **table 9**. We therefore collapsed instruments, restricted the lag range to 2–3, and reduced endogenous sets. In the corrected specification, AR(2) is insignificant, instrument count < groups, and Hansen p-values are within the acceptable 0.1–0.9 range. Where GMM diagnostics remained marginal, we corroborated signs and magnitudes using FE with Driscoll–Kraay SEs and AMG.

In **Table 9**, the dynamic panel model depicts the relationship between digital transformation, innovation culture, cultural capital, and digital media literacy besides connecting R&D intensity and carbon footprint, media coverage intensity, green financing, and environmental regulation. Digital transformation (DT) is positively and statistically significant in its effect on media coverage intensity (MCI) (0.486, $p<0.01$) and green financing (GF) (0.678, $p<0.05$), and the results indicate that digitalization strengthens the awareness of people and financial inclusion. Also, environmental regulations (ER) show positive impact on environmental policy enforcement at 1% significance level which gives evidence that technology adoption positively affects the implementation of environmental policy. Further results, excluding the mediation effects and environmental controls, indicate that an increase of one unit in digital transformation is linked to a decrease of one unit in carbon footprint ($\beta = -0.0538$; $p < 0.05$); this means that a higher digital ability is associated with more efficient use of resources and carbon footprints. The culture of innovation has mixed effects. The effects on media exposure (0.101, $p<0.01$) are statistically significant, but the effects on environmental regulations are not ($p>0.05$), suggesting that innovation investments mostly impact environmental performance directly, and behaviors related to environmental regulations are less likely to be affected but has no significant implication on green financing (-1.041) and carbon footprint (-0.0384). The negative relationships between carbon footprint and media coverage intensity and environmental regulations (-0.720, -0.419 and -0.323, $p<0.01$, respectively) prove that participation of creative sector contributes to sustainability. The finding indicates that cultural capital may not hold significant power in the context of green finance, meaning that while cultural awareness alone may not be enough to enable sustainable investment; it does require supportive financial and institutional measures. Digital media literacy (DML) is essential in enhancing sustainability as a more literate person puts out less carbon emission (-0.0904, $p<0.01$). DML also has a positive impact on the participation of the population and policy awareness (0.104 and 0.0527), but its impact on green finance is insignificant. The positive but significant correlation among MCI (0.461, $p<0.01$), GF (0.972, $p<0.01$), and ER (0.145, $p<0.01$) indicates that the high intensity of research and development leads to sustainability-oriented innovation.

Table 10 that was obtained using the dynamic panel model determines the factors behind green innovation (GI) and environmental regulations (ER). Digital transformation and green innovation exhibit minor, but significant negative association in the short-term ($\beta = -0.173$, $p < 0.01$), indicating that the costs of digital transition might outweigh environmental innovation benefits in the short term before the environmental benefits take effect in the long term. Nevertheless, the positive influence of DT on the environmental regulations (0.226, $p<0.01$) demonstrates its contribution to the reinforcement of the sustainability principles. Innovation Culture (IC) has very good positive correlation with green innovation (0.273 and 0.256, both $p<0.01$) which validates the fact that an innovative culture encourages sustainable technological advancement. The effect of IC on regulatory change is also positive and significant (0.0305, $p<0.01$). Cultural Capital (CC) has a strong positive correlation with green innovation (0.264 and 0.379, $p<0.01$), but has a negative correlation with environmental regulation (-0.357, $p<0.01$) perhaps because increased ecological awareness drives less reliance on regulation. Cultural capital significantly supports green innovation, also negatively related to the environmental regulation, suggesting that environmental awareness can lead to a decrease in formal regulatory influence. Digital Media Literacy (DML) has a positive effect on green innovation (0.147 and 0.142, $p<0.01$) but has no significant impact on environmental regulations (-0.00203). Research and Development Intensity (RDE) is also negatively associated with the green innovation (-0.0998, $p<0.01$) and positively impacted on environmental regulations (0.123, $p<0.01$). There is a positive feedback between environmental regulations and green innovation (0.528 and 0.0775, $p<0.01$), which implies reinforcement.

The mediation results show that level of intensity of media coverage and green finance partially mediate the results of the linkages of digital transformation, innovation culture and the intensity of R&D efforts with environmental indicators. The results indicate that the technology capabilities positively affect sustainability not only directly but also indirectly, by assisting in the transmission of information and access to sustainable finance.

To examine the moderating effect of institutional quality, positive interaction effects are found, indicating that stricter regulatory environments create the positive interaction effects between environmental outcomes derived from digital transformation, innovation culture and R&D intensity.

The comparison of factors that affect carbon footprint (CF) appears in **Table 11** between developing and developed countries. Several decisive variables exhibit dissimilar effects on CF between groups of developing nations and developed nations. DT introduces minimal changes to CF levels for developing and developed countries with calculated coefficients equal to 0.0121 and 0.00761, respectively. Computer technology implementation has no significant relation with reduced carbon emissions in developing and developed countries. Innovation culture (IC) presents opposing results because it lowers carbon footprints (-0.0543***) in developing countries and simultaneously raises them (0.212***) in developed nations. In developing countries, innovation culture serves as a factor for lowering carbon footprints. Innovation culture exhibits heterogeneous effects across countries. A higher level of innovation activities can help in reducing the carbon footprint in developing economies, by enabling the transition to cleaner production processes. Developed economies, on the other hand, could first see rising emissions as innovation is focused on energy-intensive research and advanced manufacturing and technology development before measurable environmental gains are realized. Yet, it leads to CF growth within developed countries because their advanced manufacturing processes consume more energy.

Table 10. Dynamic Panel Model Results

	(1)	(2)	(3)
VARIABLES	GI	GI	ER
DT	-0.0437	-0.173***	0.226***
	(0.0292)	(0.0346)	(0.0156)
IC	0.273***	0.256***	0.0305***
	(0.0253)	(0.0258)	(0.0107)
CC	0.264***	0.379***	-0.357***
	(0.0796)	(0.0824)	(0.0438)
DML	0.147***	0.142***	-0.00203
	(0.0275)	(0.0279)	(0.0307)
RDE	-0.0167	-0.0998***	0.123***
	(0.0183)	(0.0218)	(0.0100)
ER		0.528***	
		(0.0730)	
GI			0.0775***
			(0.0138)
Constant	0.834***	0.895***	0.0310
	(0.0825)	(0.0842)	(0.0678)
Observations	499	499	499
Number of countries01	20	20	20

Standard errors in parentheses

**** p<0.01, ** p<0.05, * p<0.1*

Table 11. Comparison between Developing and Developed countries

VARIABLES	(Developing Countries)	(Developed Countries)
	CF	CF
DT	0.0121	0.00761
	(0.0444)	(0.0196)
IC	-0.0543***	0.212***
	(0.0163)	(0.0457)
CC	-0.693***	0.225***
	(0.123)	(0.0592)
DML	-0.00251	-1.857***
	(0.0268)	(0.0765)
RDE	0.0601**	0.00302
	(0.0250)	(0.0190)
GI	-0.629***	-0.203***
	(0.0592)	(0.0232)
MCI	0.0461***	-0.301***
	(0.0172)	(0.0466)
GF	-0.0209***	-0.00218
	(0.00526)	(0.00320)
ER	0.444***	0.850***
	(0.104)	(0.0988)
Constant	3.882***	6.092***
	(0.174)	(0.153)
Observations	248	250
Number of countries01	10	10

Standard errors in parentheses

**** p<0.01, ** p<0.05, * p<0.1*

5. Discussion, Conclusion and Implications

5.1. *Discussion and Conclusion*

This paper explores the connections between digital transformation, innovation culture, cultural capital, digital media literacy, and R&D intensity on carbon footprint cuts and green innovation with the help of the influence of media coverage intensity and green financing as the mediators and environmental regulations as the moderators. The study provides important insights by comparing the developed and developing countries on the impact of technology, financial, and regulatory factors that influence the sustainability outcomes in the various economic settings.

The digital transformation has a considerable positive impact on the carbon footprint in developed countries (H1a accepted). This aligns with Yan *et al.* (2022), who believe that digital transformation in developed economies assists in optimal energy consumption and reduction of industrial pollution. In developing countries, however, the effect is not significant (H1 rejected), who claim that the lack of digital infrastructure and the reliance on fossil fuels render the digital solutions not very effective in terms of carbon emission reduction.

In the light of Institutional Theory, the findings indicate that high institutional quality and more robust regulatory environments in developed economies can promote very positive environmental outcomes of digital transformation. Likewise, the RBV suggests that more developed economies have better technological capacity, digital infrastructure and organizational resources to leverage and use digital transformation for carbon footprint reductions.

Carbon footprint reduction is greatly affected negatively through innovation culture in both developed and the developing world (H2a accepted). Innovation culture in the developed world leads to green technologies and investment in research and development to cut down carbon emissions. Nevertheless, in developing nations, the impact is less significant, as there is an uncertainty of the lack of resources, violation of regulations, as well as ineffective infrastructure (Liu *et al.*, 2023), which complicates the scaling of green innovations.

One interesting finding and somewhat counterintuitive is that the innovation culture increases the carbon footprint in the developed nations (H2a is rejected in this scenario). This is contrary to (Jayathilaka *et al.*, 2024) which indicates that innovations that ought to be generated by R&D can result in carbon reduction. This outcome might be explained by taking up energy-intensive green technologies (e.g., renewable energy infrastructure) at the early developmental phases of innovation. The result could be attributed to the Innovation Lifecycle Theory, which implies that innovation efforts take significant time and spend large amounts of money on research and development, and technology development of new innovations, before the environmental impact becomes visible. Likewise, the Technology Diffusion Theory argues that new green technologies take time before being disseminated across sectors. It is therefore likely that the short-run rise in carbon emissions are the transition costs of innovation, while long-term knowledge spillovers and technology diffusion are likely to lead to better environmental outcomes.

These results further align with Institutional theory by showing that a policy context supportive of innovation drives innovation activities, and with RBV by showing that R&D capability and innovation resources are valuable strategic assets that support sustainability transitions.

The impact of cultural capital on the carbon footprint reduction is significant in developed nations (H3a accepted) because the high cultural capital facilitates the appearance of the green innovations and reception of greener technologies (Jayathilaka *et al.*, 2024). In less developed countries, the effect is not so significant. Cultural capital is ineffective in mitigating carbon emissions due to low cultural capital, absence of environmental education, and other barriers to societal enjoyment in terms of commitments to the sustainability (Wan, 2024). This implies that to maximize the benefits of cultural capital in sustainability transitions, the role of environmental education and solid societal values is mandatory. The result underscores the relevance of institutional theory, notably concerning the influence on the sustainability behavior of environmental education and institutional support, and strengthens RBV as a theoretical lens emphasizing the role of cultural knowledge and human capital as strategic national resources in fostering green innovations.

Digital media literacy has a role to play in the reduction of carbon footprint in the developed and developing nations with H4a accepted. This observation corroborates Pangrazio & Sefton-Green (2020) who demonstrate that digital media literacy facilitates sustainability awareness and responsible consumption. In developing economies, it is less significant, because of the misinformation, poor standards of digital literacy training, and poor digital platforms. This highlights the significance of the availability of sound environmental data and robust digital literacy systems in developing countries to eco-friendly sustainability results. The results suggest that institutions supporting digital education are more effective for boosting digital literacy in the field of sustainability. For the RBV, digital competencies are intangible assets with high value for supporting environmental innovation and decision-making.

Intensity of R&D plays a significant role in carbon footprint reduction in developed nations (H5a accepted) because investments in high R&D allow the realization of low-carbon technologies and green innovations (Cacciuttolo *et al.*, 2023). However, R&D intensity is less effective in developing countries because of the financial constraint and scarcity of R&D resources. This indicates that more investments on R&D in the developing countries, as well as better accessibility to green technologies are required to realize carbon reduction. The results are consistent with the RBV concept, which highlights that research capacity is one of the most powerful strategic resources in the quest to sustainable competitiveness, with the support of a regulatory framework that enhances the effectiveness of R&D investments in environmental goals.

The positive impact of digital transformation on green innovation is high in both developing and developed nations (H1b accepted). This is consistent with Jayathilaka *et al.* (2024), who discovered that green innovation is fast tracked through digital transformation as it streamlines operations and allows the creation of technological solutions that are environmentally friendly. Although the impact is greater in developed nations, the digital transformation continues to be a very serious responsibility towards the promotion of green innovation in developing nations, though at a slower rate due to the limitation of infrastructures.

The positive influence of innovation culture on the green innovation is significant in both developed and developing countries (H2b accepted). In developed economies, the green technologies and green manufacturing are supported by investments in R&D and innovation-oriented policies. However, in the developing countries, the absence of the regulatory support and financial resources control their capacity to scale green innovation.

In developed countries, cultural capital is a major driver of green innovation (H3b accepted) because well-developed cultural values and educational systems generate the creation of environmentally friendly innovation. In the developing nations, the effects are usually less well because of low environmental education and cultural obstacles.

Digital media literacy also plays an important role in green innovation, both in developed and developing nations (H4b accepted). Green innovation is faster through high digital media literacy in the developed countries since it encourages ecological actions and supports policies (Suwandi, 2022). In developing nations though, there is a barrier to green innovation by means of digital media literacy caused by low-quality digital literacy and misinformation.

The intensity of R&D positively contributes to green innovation in developed countries (H5b accepted) but its impact is not as great in developing countries. The developed nations use the R&D investments to create low-carbon technology and practices that are sustainable (Ding *et al.*, 2022). In the case of developing countries, financial barriers and institutional barriers prevent effective green innovation through R&D (Wang *et al.*, 2021).

The association among innovation culture, digital transformation, cultural capital, and intensity of R&D on carbon footprint reduction and green innovation in developed countries is significantly mediated by media coverage intensity (H6 accepted). This observation is consistent with previous researchers (Huang *et al.*, 2021; Ren *et al.*, 2023) that attests to the societal pressure created by media exposure to demand sustainability measures. The mediating role of the media coverage intensity is less strong in developing countries because of poor media infrastructure and restricted access by people. The mediating effect of media coverage intensity shows that information dissemination and public awareness increase the relationship between technological capacity and sustainability outcomes, as well as between innovativeness and sustainability outcomes, thus giving evidence to the institutional mechanisms suggested by Institutional Theory.

In developed countries, the relationship between innovation culture, digital transformation, and digital media literacy and R&D intensive over reduction of carbon footprint and green innovation is mediated by green financing significantly (H7 accepted). This coincides with previous researchers (Cai *et al.*, 2025a; Sun & He, 2023; Ye & Dela, 2023) who believe that sustainable investment practices are triggered by green financing. In developing economies, the impact is lower caused by financial constraints and ineffective regulatory frameworks. Likewise, the mediating role of green finance indicates that green finance helps facilitate RBV by establishing that contact between technological capability and environmental performance is enabled by financial resources.

In the developed nations, environmental policies moderate the influence of green innovation and the decrease of carbon footprint (H8 accepted). This would be in line with Lv *et al.* (2021), who show that rigid environmental policy fast-tracks green technology and sustainability in an already developed economy. In developing economies, the green transition is slowed by poor regulation structures and non-compliance (Gao & Dong, 2022). The research finding indicates that the role of digital transformation, innovation culture, cultural capital, digital media literacy, and R&D intensity in loss of carbon footprint and green innovation in developed and developing nations are different. Additionally, the effect of environmental regulations as a major moderating factor further supports the Institutional Theory, which emphasizes that the formal institutions increase the effectiveness of organizational resources and technological capabilities in the process of supporting sustainability.

Overall, the results have shown that digital transformation, innovation culture, cultural capital, digital media literacy, and R&D intensity are factors which impact sustainability outcomes, albeit in different ways across developed and developing economies. The study also shows that the intensity of media coverage works as a mediating factor in these relationships and that environmental regulation enhances their impact (Cai *et al.*, 2025b). This study contributes to the existing sustainability literature by applying the Institutional Theory along with the Resource-Based View to provide a comparative macro-level discussion of how strategic resources and institutional conditions work together to influence carbon footprint reduction and green innovation across countries.

The comparative part of the analysis also shows that when considering the sources of differences across developed and developing economies, institutional quality, digital infrastructure, financial development, industrial structure, and energy dependence are the main factors explaining the disparities. In general, developed economies have higher financial maturity levels that enable digital transformation and innovative resources to yield higher sustainability benefits because of their stronger regulatory enforcement and their more and advanced technological capabilities. Developing economies, however, are still confronted with institutional and financial barriers which restrict the impact of these strategic resources.

5.2. *Implications*

The findings suggest that sustainability policies should be tailored according to countries' institutional and economic conditions. For developed economies, enhancing digital infrastructure, promoting green finance markets, fostering strong advanced R&D investments, and keeping environmental regulation stringent are important ways to boost green innovation and carbon reduction. In developing economies, the emphasis should shift to institutional development, digital access, and environmental governance, access to green finance, and research capacity and digital skills. These priorities will allow developing countries to convert technologies into better sustainability outcomes.

In the context of policymaking, this study proposes country-specific sustainability initiatives that apply to countries depending on their economic potentials and readiness of institutions. The developed countries must develop the following requirements to enhance green financing framework, strengthen environmental regulations, and increase digital networks to augment the initiatives in reduction of carbon emission and sustainable development (Cai *et al.*, 2024). In contrast, the developing economies should focus on investments in financial mechanisms, international cooperation, and local capabilities of digital skills, cultural interactions, and research-based innovation. In developing nations, the analysis shows that the move to adopt sustainability efforts relies greatly on enhancing the quality of media coverage and the access to green finance. The study further underscores the importance of expanding institutional quality in tandem with investments in the digital infrastructure, green finance and innovation ecosystem instead of focusing on each single policy area separately.

5.3. *Limitations and Suggestions for Future Research*

Although this study presents substantial contributions, it is also facing some limitations that should be admitted and improved in future works. This research uses secondary sources, and these are credible international datasets including the WDI, OECD, and Eurostat. These sources, however, might be inconsistent and have reporting holes across countries especially in developing countries and this may affect the strength of the findings. In further studies, the researcher might consider the primary data through the use of survey data of firms or local cases to collect more structured and correct information about how digital transformation and financial tools contribute to sustainability.

Another limitation relates to the use of proxy variables for green innovation, digital transformation, cultural capital, digital media literacy, media coverage intensity, and environmental regulations. These proxies provided compatibility with international data and consistency between time periods within the length of the study, but they may not adequately reflect the multidimensional nature of the proposed theoretical constructs. Therefore, the results cannot be interpreted as a direct measurement of these concepts but instead as a reflection of macro-level relationships.

The next weakness is the size of the sample: the research has 20 countries 10 developed and 10 developing. Although the sample offers meaningful findings, the findings cannot be extended to small economies or other regions that have distinct sustainability issues. Further research must increase the number of countries captured in the sample especially those with unique economic and environmental development to capture a global and universal perspective of the dynamics of sustainability. Moreover, this study makes use of macro-level data and does not distinguish between the impact on different sectors, like manufacturing, energy, or transportation. Research on sector-specific effects caused by the digital transformation, innovation culture, and investments in the field of financial activities might provide a deeper understanding of the specific drivers and inhibitors related to various industries. Further research is needed to investigate how these variables influence sustainability transitions in specific industries in order to gain a clearer picture on the dynamics in action.

The two-step System-GMM is suitable for the case of reverse causality, omitted variables, and dynamic relationships, but it is a methodological restriction to use it in a country panel of 20 countries. To enhance the credibility of this finding, robustness analysis with alternative estimation methods was carried out, but further analysis in the future employing larger international panels and other estimation methods is needed. To supplement the macro-level evidence provided in this research, future study should focus on larger country samples, a variety of measures for constructs of sustainability, and sector- or firm-level data sets. Understanding non-linear relationships, regional spillover effects, and longer time horizons of technology diffusion would further improve availability of knowledge about sustainability transitions in different institutional contexts.

Conflict of interest

The Authors have no known financial interests or personal relationships that might influence the work reported here.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Credit authorship contribution statement

All authors contributed to the study's conception and design. M.A: material preparation, conceptualization, writing, and revising. U.A.B : methodology, modeling, supervision, and software. M.H: Methodology, modeling, and software. Y.Y.G: Y.G & S.M: funding acquisition, investigation, writing-reviewing, and Discussion, introduction. methodology, modeling, funding, and software.

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Appendix A

Country-wise Descriptive Statistics

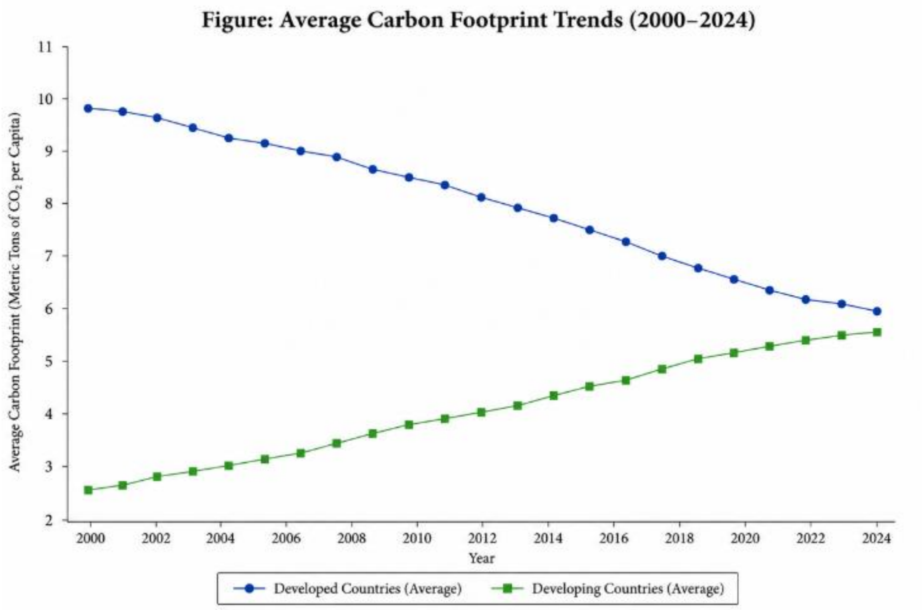
Table A. Country-wise Descriptive Statistics (Mean Values)

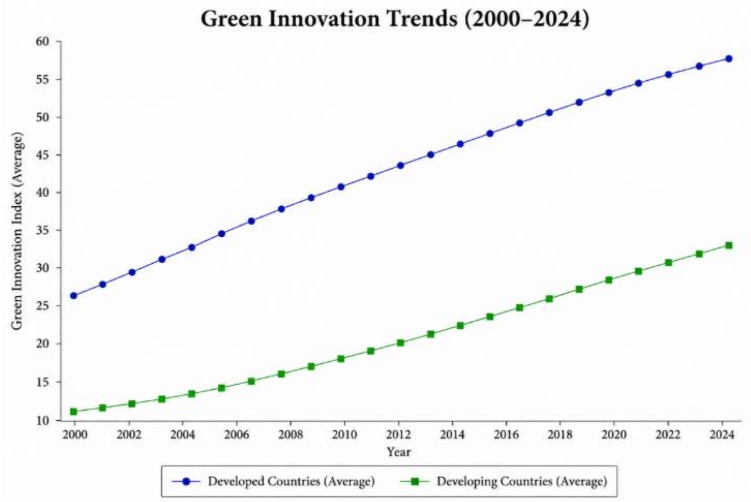
Country	CF	GI	DT	IC	CC	DML	RDE	MCI	GF	ER
Germany	18.52	29.84	82.31	3.12	3.46	84.75	4621	91.32	125.44	5.82
United States	22.47	18.92	80.46	3.05	3.28	81.93	4413	90.58	148.73	5.63
United Kingdom	15.73	38.41	84.56	2.98	3.61	86.74	4389	93.18	118.56	5.79
Sweden	8.65	56.82	86.27	3.48	3.84	89.53	5214	94.41	96.42	5.94
Japan	20.74	16.38	78.95	3.34	3.25	82.16	5127	90.87	132.74	5.56
South Korea	23.18	11.84	83.47	4.01	3.19	85.26	4983	92.65	121.83	5.48
France	12.43	33.25	81.74	2.89	3.55	84.38	4438	91.71	109.53	5.71
Canada	19.36	27.54	79.81	2.94	3.42	82.44	4312	89.95	134.81	5.66
Netherlands	13.54	31.62	85.18	3.11	3.67	87.52	4561	93.64	115.62	5.85
Australia	21.48	24.36	80.63	2.87	3.39	83.87	4198	90.43	129.17	5.54
China	26.85	14.75	58.32	2.18	2.14	55.28	1386	70.15	87.64	3.94
India	28.64	21.53	41.84	0.82	1.76	29.37	264	46.52	42.73	3.12
Brazil	17.36	45.81	55.63	1.46	2.21	47.82	894	64.37	58.19	3.76
South Africa	31.42	10.52	49.71	0.91	1.94	43.66	506	58.41	37.56	3.41
Mexico	19.84	18.47	56.24	1.38	2.08	51.63	748	61.28	53.18	3.65
Indonesia	24.51	30.18	46.92	1.11	1.87	39.75	402	54.63	46.81	3.29
Nigeria	33.75	8.64	28.54	0.46	1.42	18.36	118	29.48	21.34	2.64
Vietnam	21.43	26.71	52.36	1.27	1.95	44.28	536	59.81	39.62	3.48
Kenya	15.81	41.28	33.49	0.69	1.58	25.41	173	36.94	24.57	2.91
Egypt	22.94	12.83	39.58	0.88	1.74	31.82	287	42.17	33.49	3.08

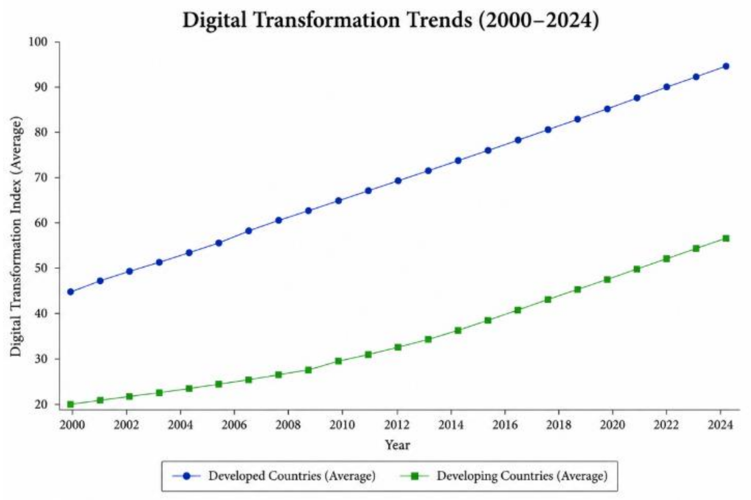
Appendix B

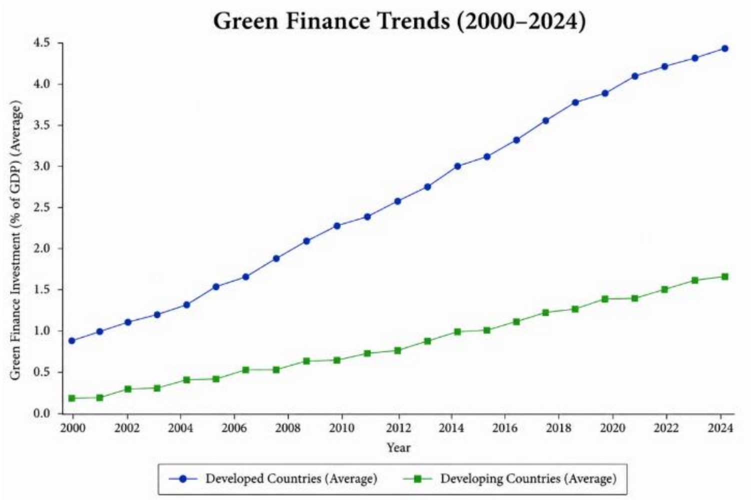
Trend Plots

To complement the descriptive statistics, Figures present the temporal trends of the major study variables. The figures compare the average values for developed and developing countries during 2000–2024 and provide a visual overview of changes in sustainability-related indicators over time.




Green Innovation Trends (2000–2024)
Green Innovation Index (Average)
Year
Developed Countries (Average)
Developing Countries (Average)


Digital Transformation Trends (2000–2024)
Digital Transformation Index (Average)
Year
Developed Countries (Average)
Developing Countries (Average)


Green Finance Trends (2000–2024)
Green Finance Investment (% of GDP) (Average)
Year
Developed Countries (Average)
Developing Countries (Average)