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Research article

Estimating digital adaptation and governance in international businesses by targeting environmental sustainability

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ABSTRACT

By aiming at multidimensional environmental sustainability, international firms can venture into digital adaptation for better environmental quality. This study acquired data from Europe, Australia, and the United States of America for five years (2018–2023), comprising 2606 international firms. Robust machine learning panel data analysis uncovered the significant role of digital transformation on environmental sustainability impacting societies. Digital transformation is estimated using capital expenditures, research and development expenses, and cybersecurity policies that encompass technological investments, strategic readiness, and digital governance. The regression outcomes reveal wholistic understanding regarding the role of digital initiatives in environmental sustainability while machine learning provides relative importance of policy options. Both methods address strategic integration and tension between economic decisions and sustainable goals. This study highlighted the importance of digitalization and sustainable development in the context of business internationalization that provides actionable insights into business and policy management of global business sustainability while enhancing environmental quality.

1. Introduction

In an attempt to abate climate change, national efforts must motivate individuals towards sustainable behavior. This study is interlinking the digitization phenomenon on the environmentally sustainable behavior of international businesses. This effort can help reduce pressures and use digital transformation initiatives with sustainable development goals (Ciulli and Kolk, 2023; Han and Wei, 2025). In this examination, it is proposed that digital technologies can help in reshaping the traditional business models and open new opportunities in global value chains.

Exploring the role of digital transformation, it is noted that it can help in improving monitoring and managing business functions. Use of Internet of Things (IoT) sensors can track resource consumption, carbon emissions, and waste production in real time (Kache and Seuring, 2017). Visibility enhancement helps better decision making in response to sustainability related challenges. Similarly, the use of blockchain technology can revolutionize the supply chain transparency. Firms can track the origin of raw materials and ensure regulatory compliance (Sanguineti et al., 2023). Machine learning and text analysis also contribute to environmentally sustainable innovation (Huang et al., 2025). At firm level it will help build stakeholder trust and demonstrate their commitment towards sustainability. Further, artificial intelligence (AI) and machine learning (ML) are instrumental in optimizing the resources. They help international businesses to predict maintenance needs and reduce energy consumption (Liu et al., 2024). Lastly, cloud computing can enable sustainable practices in international business by providing centralized data storage and processing units. It helps in reducing environmental impact (Gammelgaard and Nowicka, 2023).

The merits of these technologies are only accessible when the business has started the process of digitization within their operations (Luo and Zahra, 2023). Digitization helps in leveraging these sophisticated technologies (Nambisan and Luo, 2021). While digitization itself has some environmental challenges, it is energy intensive and it leads to increased electronic waste (Dwivedi et al., 2023), it can still help

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businesses transform because of its capacity-building mechanism and leverage scalable processes (Tsou and Chen, 2023). It can also help international businesses to engage with sustainability-focused stakeholders. Use of these platforms can give a good signal that the business is adopting environmental initiatives (Ciulli and Kolk, 2023). Digitization gains go beyond profitability towards innovation for sustainable businesses. The circular economy initiatives and sustainable product design are only possible with digital technologies (Inigo et al., 2020). It also brings smaller businesses to a level playing field against large multinational corporations by democratizing the sustainable practices (Denicolai et al., 2021). There will be an acceleration in the integration of digitization and sustainability in international businesses. The emerging technologies are assisting business operations which are located at distant locations (P. Xu et al., 2023).

In order to stay competitive, now businesses need to develop new capabilities and rethink their approach to environmental sustainability. Their growth depends on their ability to effectively integrate digital solutions to the environmental challenges (George and Schillebeeckx, 2022). The rapid evolution of the business landscape is possible because of leveraging digital technologies. Business are applying digital solutions, setting cybersecurity protocols, and increasing capital investments that help them meet their environmental performance targets (George and Schillebeeckx, 2022) but it is evident that there is little literature on estimating the role of digitization practices on multiple indicators of environmental quality in international business perspectives.

This study breaks down the multifaceted problem. First, in the context of digitization, it requires a significant increase in capital expenditure and research and development (R&D) investment, however, their effect on sustainable practices in international businesses is unclear empirically (Luo and Zahra, 2023). Secondly, the inclusion of corporate governance mechanisms in the form of cybersecurity policy and board diversity required deeper investigation (Al-Tabbaa et al., 2023). Thirdly, the inclusion of important environmental quality indicators and firm specific controls like corporate governance, market risk, and profitability were required to form a stable relationship assessment. Finally, it is required to develop rankings of the policy instruments in terms of their effectiveness on the environmental indicators.

This study is designed to add emphasis on the digital transformation on sustainable development at firm and corporate level. The sample included the firms which describe themselves as trading firms to explore the unique perspective on how these globally linked businesses can ensure environmental sustainability while managing their businesses across multiple jurisdictions like emissions, corporate social responsibility (CSR), resource use, and recycling. Hence the objective of the study is to examine the relationship between different firm level digital transformation measures like investments, R&D, digital governance, and security frameworks on multiple environmental quality indicators. This study also ranks the policy options to optimize environmental performance improvement strategy. This concluded by forming the research question of the study as '*how do international business firms' digital transformation strategy impact environmental quality indicators and what is optimal policy option sequence in improving environmental performance?*'. This study comes under Sustainable Development Goals 12, 13, and 17.

This study adds to the emerging discourse on digital sustainability in businesses (Dwivedi et al., 2023; Lohmer et al., 2024) in a cross-continental perspective to explore how digital transformation is shaping environmental goals. Currently the quantitative assessment of digitization on sustainability at a cross country and cross sector level is scarce (Jiang et al., 2024). The existing literature on Resource Based View (RBV), Institutional Theory and Organizational Change theory have explained digital transformation at firm level but its role in international business is underexplored (Adomako and Tran, 2024). The inclusion of digital governance as a strategy and CSR as an environmental outcome lack comprehensive evidence in literature and the prior studies overlook the multidimensional interaction between digital transformation and environmental performance. Empirical studies also lack systematic thinking to rank environmental policy options using machine learning to ensure heightened policy effectiveness. The gaps addressed in the study are based on a cross-continental perspective with a holistic approach to digitization and environmental performance (O'Connell et al., 2025). Methodologically, this study used robust methodology by integrating regression analysis and random forest estimation. Both complement in raking the importance and effectiveness of the independent variables.

The study is organized in the following manner. After the introduction, this study presents the literature review in Section 2. Section 3 reports the list of methods used to fulfill the objectives. This section is followed by results and discussions in section 4.

2. Literature review

2.1. Theoretical review

Digital transformation is emerging as a transformative force that can reshape business practices with its consequential societal and environmental dynamics. Within the domain of technological advancement, technological transformation integrates digital technologies into business processes that fosters innovation, operational efficiency, and organizational development (Melville, 2010). This study uses multidimensional perspective to link digital transformation with environmental performance and provides the theoretical underpinnings in this section.

2.1.1. Digital transformation and environmental performance

To assess digital transformation this study has used a multiprong strategy whereby capital expenditures are used as strategic transformation, R&D expenditures are used as strategic investments, and Cybersecurity disclosures are used as digital governance. Discussing capital expenditures, the shared value theory explains that capital investments with increased energy use and infrastructure change led emissions (Jiang et al., 2024) while the long term stability is expected under stakeholder theory (Porter and Kramer, 2011). The capital investments do lead to short term environmental tradeoffs per the punctuated equilibrium model (Romanelli and Tushman, 1994).

For the case of R&D, under eco-innovation theory, it can reduce emissions and resource efficiency. Evolutionary economics and ecological modernization theories advocate that R&D based technological advancements are resource efficient (Adomako and Tran, 2024; Geissdoerfer et al., 2017a) but the innovation intensity of R&D may temporarily supersede economic and technical growth over CSR initiatives (Jensen, 2002).

Digital governance has a role to play in environment stewardship is explained under legitimacy and signaling theories. Robust disclosures can signal responsible governance and also facilitate energy efficiency (O'Connell et al., 2025; Rauf et al., 2024; Shrivastava, 1995). Digital governance also improves the dynamic capabilities to improve waste recycling (Teece, 2007).

2.1.2. Controlling factors and environmental performance

This study uses the dual narrative of impact of size on environmental performance whereby larger firms can use scale effect theory leading to higher energy use and emissions (Cole et al., 2013; Dinda, 2004). For global expansion these firms stick to resource based view (RBV) to optimize the resource requirements leading to higher demand of resources (Hart and Dowell, 2011) but institutional theory also suggests that larger firms are more exposed to regulatory and societal pressures to adopt sustainable practices. This engages them into advanced resource management capabilities which are affordable at economies of scale like waste management (Aragón-Correa et al., 2016; King and Lenox, 2002).

Profitability is used as a critical enabler for environmental performance for firms. This is expected using resource efficiency and Porter hypothesis, whereby profitable firms can invest in cleaner and efficient technologies that can reduce energy demand and emissions (Palmer, 2017). This relationship is also explained using the pay to be green hypothesis in which profitable firms have higher financial capacity to finance environmental stewardship (Ambec and Lanoie, 2008) but the duality of effect is coined to organizational slack theory whereby firms acquire abundant resources and deprioritize cost-saving measures (Melnyk et al., 2003).

Market risk compels firms to tradeoff between short-term stability and long-term environmental goals. Within risk management, theory states that volatility drives firms to focus on operational reliability at expense of energy efficiency (Marcus and Fremeth, 2009). Similarly, slack resources theory explains the risk leading to lower corporate social responsibility because of diversion of discretionary expenditures towards risk management (Jo and Na, 2012).

Corporate board diversity is well versed in literature with respect to environmental outcomes. It showed an increase in CSR and reduced emissions per resource dependence and upper echelon theories (Bear et al., 2010; Glass et al., 2015). The link between board diversity and resource demand is complicated, it can be linked to the increase in demand because of resource intensive digital innovation strategies (Miller and Triana, 2009).

Organizational, resource based, and institutional theories are used to form the interaction of these variables is proposing a sound strategy for environmental performance to develop critical insights and policy.

2.2. Empirical review

In this section the empirical evidence is presented for the relationships between the selected independent variables and the environmental performance of the firms.

In the case of digital transformation, empirical studies have used several indicators are firm level. First is the capital expenditure which includes the purchase of digital assets and supportive physical assets (Brunjolfsson et al., 2014). When transitioning to digital technology, capital expenditure plays an important role in developing the infrastructure and, consequently, environmental performance in the case of Chinese firms (Wen et al., 2021). Digital transformation in China had shown a reduction in waste and emissions between 2010 and 2018 (Wang et al., 2022) but it can increase resource and energy use in manufacturing firms (Chen et al., 2020). Digital technologies had also helped in eco-innovations for solid waste management in Indian firms (Rena et al., 2022). Hence, investing in modern and sustainable technologies is expected to enhance firms' capacity for energy efficiency, pollution abatement, and resource optimization.

H1. Capital expenditures have a significant effect on environmental performance

Empirical studies have shown that this strategic capital allocation can improve environmental outcomes (Broccardo et al., 2023). Developing clean or digital technology infrastructure require investment which will improve their resource use (Liu et al., 2023). Similarly, firm level research and development investments also have shown their role in driving sustainable innovation and developing efficient processes (Inigo et al., 2020).

Higher R&D intensity leads to lower environmental concerns or externalities (Kabongo and Okpara, 2013) and it also increases the digital capability of the firms (Tambe and Hitt, 2012). It can help limit carbon emissions in developed countries (Jiang et al., 2024). R&D also helps in reducing emissions without compromising the firm performance (Verma et al., 2022). R&D investments improves environmental performance in terms of energy and carbon emissions in G-6 country firms (Alam et al., 2019). This digital transformation can reduce the carbon intensity in the transportation industry globally (Huang et al., 2023). These investments also help firms to increase CSR specialization of the firms as confirmed by 1957 multi country firms over 16 year data (Fu et al., 2020). This result is significant in the manufacturing industries (Padgett and Galan, 2010). A study in the case of China showed that R&D has the potential to reduce the energy intensity within industries (Huang and Chen, 2020) and, in the case of organization of economic cooperation and development (OECD) countries, R&D does increase energy consumption but it also transitions from non-renewable to renewable energy (Churchill et al., 2021). Hence, research and development activities that foster eco-innovation and cleaner production processes contribute to reduced environmental footprints.

H2. R&D investments have a significant effect on environmental performance

The disclosure of cybersecurity policies indicates the digitization maturity of the firms. The need for this security policy relies on the size and sensitivity of the digital infrastructure which the business was to sustain and secure. Bharadwaj et al. (2013) stated that cybersecurity disclosures are indicative of high digital integration of the business. It measures the digital governance of the businesses (Gordon et al., 2018; Shaikh and Siponen, 2024). Collectively all these indicators present themselves as a wholistic indicator of digital transformation process of business (Westerman et al., 2014). Cybersecurity reduces the carbon footprint and makes data centers energy efficient linking with the Economic, Social, and Governance (ESG) goals (Directors Institute, 2024). It supports digital governance in achieving sustainable business practices (Achuthan et al., 2025). Hence, transparent disclosure of cybersecurity practices signals stronger digital governance and resilience. It supports responsible data management, regulatory compliance, and sustainable operations.

H3. Cybersecurity disclosure has a significant effect on environmental performance

While discussing controlling factors, this study included market risk beta as the first controlling factor. Studies showed that market risk identifies how businesses align themselves for sustainability initiatives (George et al., 2023). According to this study, stable firms can commit themselves to long-term commitments. Further, there is negative association between market risk and environmental disclosures of the firms (Benlemlih et al., 2018). Several theories like risk management theory, organizational behavior under uncertainty, operational inflexibility, and resource dependence theory explain the way market risk can explain the environmental performance of firms (Anton et al., 2025; Berrone and Gomes-Mejia, 2009; Sharfman and Fernando, 2008; Zhang et al., 2025). Therefore, greater gender diversity in boards enhances decision making quality, stakeholder orientation, and sustainability oversight which are linked to environmental outcomes. For the context of governance, this study had included board diversity as a controlling factor. It is noted in literature that diverse boards tend to place higher emphasis on environmental practices (Cordeiro et al., 2020; Dhar et al., 2024; Gavana et al., 2024; Lu and Herremans, 2019). Having women on boards are more proactive in forming environmental strategies (Xie et al., 2020). Studies have coined the stakeholder and resource dependence theory that links board diversity with the environmental performance of the firms (Bear et al., 2010; Post et al., 2011). For the case of 865 publicly listed firms in the United States of America (USA), which are more polluting, board diversity can help in forming stringent environmental policy (Li et al., 2017). For the firms which are producing final goods, diversity of boards improves their CSR performance and making them competitive in the industry (Harjoto et al., 2015). Board diversity of multiple types has shown its effect on increasing the technical efficiency of the firm in managing their resources (Ali et al., 2021).

H4. Board diversity has a significant effect on environmental performance

Similarly, profitability in the form of Earnings Before Interest and Taxes (EBIT) has been used. It is noted that profitable businesses can allocate more resources for environmental initiatives (Ciulli and Kolk, 2023; Yadav et al., 2017). Study by DeCanio and Watkins (1998) also confirmed that, on the contrary to the neoclassical theory that energy efficiency leads to profitability, the results showed that firm characteristics affect the decision of the firm to adapt to energy efficient measures. There is a positive link between the profitability and environmental performance of the companies (Ali and Shah, 2024; Russo and Fouts, 1997; Zhang et al., 2025). Profitable firms have higher financial capacity to be green. The theories like resource efficiency and Porter hypothesis explain the link of profitability with environmental performance (Palmer, 2017). Further financial constraint firms tend to have higher carbon emissions as confirmed from a 1536 sample study across 2008 to 2019 in the USA (Rehman et al., 2023). Hence, financially stable firms have access to slack resources for green technology investment, CSR strategies, and long-term environmental initiatives.

H5. Profitability has a significant effect on environmental performance

Further, larger firms have more resources to adapt to environmental management systems (Al-Tabbaa et al., 2023) which generates the positive relationship with environmental performance (Younis and Sundarakani, 2020) as they have financial advantage in driving environmental innovation (Andries and Stephan, 2019). Larger firms face fewer barriers to adapt the green supply chain practices, hence show better environmental performance (Balasubramanian et al., 2020; Younis and Sundarakani, 2020). Larger firms can do the green external integration faster because of their lower time to market green goods (Song et al., 2017). Larger firms based on the scale effect theory are able to produce more which lead to more use of energy and resources and consequently increase in emissions at absolute levels (Cole et al., 2013; Dinda, 2004). Larger firms have larger boards with diverse expertise which help them to improve environmental performance (de Villiers et al., 2011). Therefore, firms that face high financial, operational, or regulatory risks are constrained in their environmental initiatives or are compelled to adopt more sustainable practices to mitigate reputational and compliance risks.

H6. Risks have a significant effect on environmental performance

2.3. Critical overview

Despite the presence of studies that link digital advancement to environmental performance, several gaps are pointed out by this study. First is that the multidimensional and multi context assessment of digital transformation is underexplored. Secondly, there is a dearth of studies focusing on digital governance and its environmental effects. Thirdly, most of the empirical studies often used a single indicator of Carbon Dioxide (CO_2) as a determinant of environmental quality (Delmas and Blass, 2010) but this study added other indicators; some are antecedents like energy and resource use, some are governance based like CSR strategy score and intervention, or commitment based like waste management at firm level. The inclusion of controlling factors to encompass risk, profitability, scale effect, and governance which improves the robustness of the empirical assessment. Lastly this study includes the advanced methodological setup that provides robust marginal impacts along with their importances which enables policy makers to strategize digital transformation.

3. Methodology

3.1. Variables and data sources

This study has access the Eikon database of firms listed in for Europe, the United States of America (USA), and Australia which led to selection of 30,719 firms. The sectors of the firms are then filtered to exclude sectors like the public sector, real estate etc., which, in turn, led to short listings of firms at 15,310. The selection of international firms is based on the use of the terms like 'trade', 'import' or 'export' in the firm description. This criterion led to the selection of 2606 companies.

The selected region of Europe, America, and Australia majorly constitute of developed countries which steer the global business and environmental dynamics. This region is a major energy consumer and a significant contributor to emissions because of their advanced industrial and resource-intensive practices (Faris, 2023). This region is also known as the Global North with less constraints with respect to resources and developmental priorities (Stanislavska et al., 2023). Understanding the behavior of these firms helps to form benchmarking for less developed economies. The examination of this region helps to focus on businesses working in well-established regulatory frameworks, with technological capabilities and access to the latest digital transformation tools (Najam, 2005). The outcome will enable them to lead the global trend towards climate change abatement (UN, 2022). This study has targeted sectors like basic materials, consumer cyclicals, consumer non-cyclicals, energy, healthcare, industrials, and technology, and dropped the sectors such as real estate and utilities. The exclusion of these two specific sectors was because both are mostly based on immovable assets, are often government owned, and are heavily regulated. For utilities, the transformation is dictated by government policies and for real estate the transformation is dictated by market demand rather than private sector initiatives. This means the dynamics are less flexible and are guided by regulatory mandates rather than corporate strategies thus making them less suitable. Furthermore, these sectors had too few observations after adjusting for missing values.

Fig. 1 plots the country-wise count of companies which are included in the sample. Currently there are 23 countries included in the sample that have the required data available. Further, Fig. 2 shows the associations of the firm descriptions related to international trade. The clustering of the keywords shows that most of the firms are from retail and goods producers linked to distribution and logistics.

Since it is unbalanced data, the exact sample of number of firms included varies across the dependent variables based on the missing values. The time period of the data is 2019–2023. The data is acquired from London Stock Exchange Group (LSEG) Eikon database which had compiled comprehensive financial data.

Table 1 provides the list of variables selected from the financial statements/annual reports of firms acquired from the Eikon database. Here CO2, CSR, EN, RES, and WASTE are the dependent variables representing the environmental performance of the firms. At country level, a study by Wolf et al. (2022) linked these variables to environmental performance. Richter and Schiersch (2017) stated that CO_2 is the direct measure of a firms' environmental footprint also reflecting in their energy utilization and waste production. Hence, this study has selected CO_2 emissions scope 1 and scope 2 which are related to firms' internal production activities, while scope 3 emissions measure how upstream and downstream utilization of the products and services. The CSR strategy score presents the firm's strategy to cater to the environment beyond mere compliance (Reverte, 2009). Energy and resource use are quantified indicators of a firm's consumption patterns representing efficiency in operations and indicates a potential area for optimization (Lankoski, 2016). Per environmental economics, higher resource or energy use my lead to consequential emissions or pollution increase (Wiredu et al., 2025). Waste recycling rate represents the firm's approach towards a circular economy and waste management (Geissdoerfer et al., 2017a). The independent variables which include CAPEX, CYBER, and R&D as indicators for digitization at strategic expenditures, governance, and innovation levels. Remaining are the control variables covering profitability, risk, and governance.

3.2. Equations

Equations (1)–(5) are the equations for the estimation of the models to meet the research objectives; each equation is using a different dimension of environmental performance. All these models have included the country and sector dummies account for country and sector

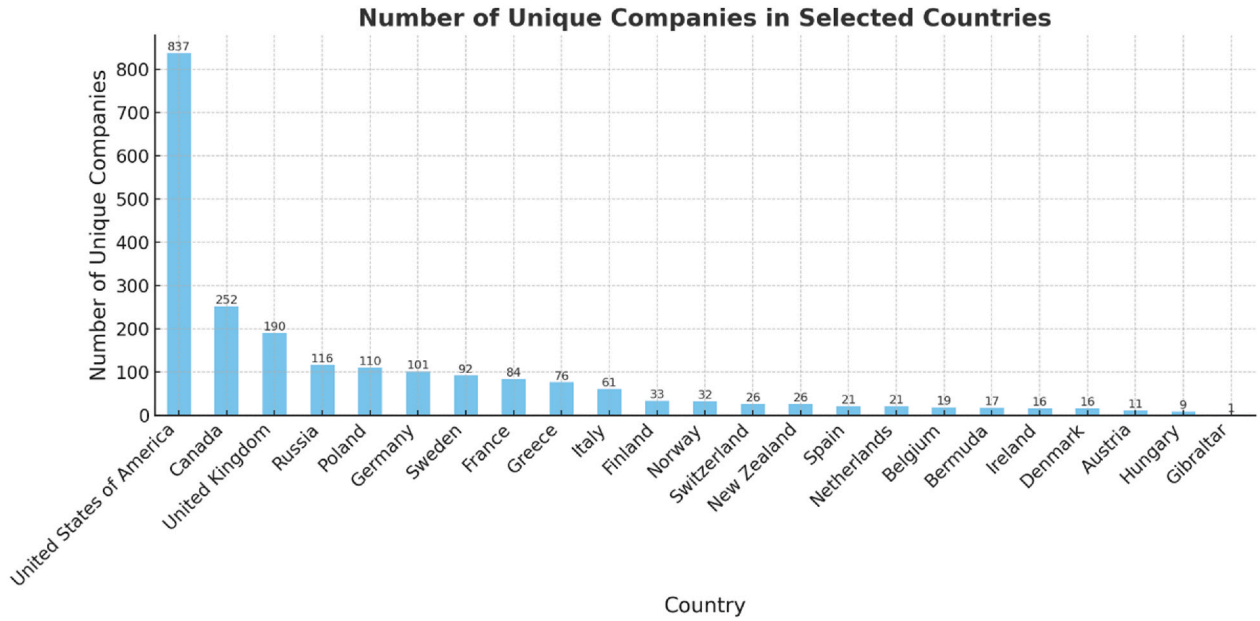

Fig. 1. – Firms included in the sample.
Source: Self Constructed

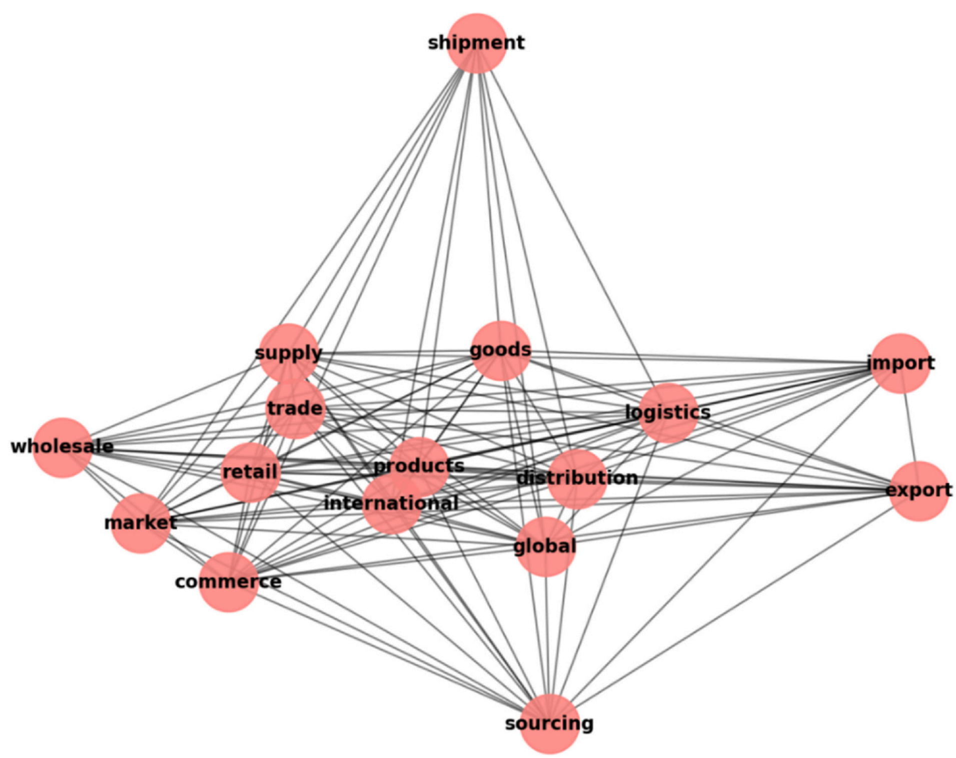

Fig. 2. – Common keywords and their associations from firm descriptions.
Source: Self Constructed

heterogeneity in the models. In the equations the subscript 'l' represent that these variables are transformed into logarithmic form. The slope coefficients β_j and δ_k are representing the countries and sector respectively. They are absorbing the unobserved heterogeneity in the data by altering the intercept with an assumption that the country and sector specific traits are homogenous across the proposed variables of the model. ε_{it} is the random error term different for each equation.

$$lCO2_{it} = \alpha_{00} + \alpha_{01} lCAPEX_{it} + \alpha_{02} CYBER_{it} + \alpha_{03} RND_{it} + \alpha_{04} BDIV_{it} + \alpha_{05} EBIT_{it} + \alpha_{06} SIZE_{it} + \sum_{j}^{n} \beta_{0j} Country_{it} + \sum_{k}^{m} \delta_{0k} Sector_{it} + \varepsilon_{0it} \quad (1)$$

Table 1
Variable and data sources.

Variable Name (Symbol)	Definition (Units)	Source
Risk Beta (BETA)	Capital Asset Pricing Model (CAPM) Beta measures the relative change (covariance) in firm stocks relative to the market.	LSEG Eikon
CO_2 Emissions (CO2)	Total CO_2 emissions in tones sum of scope 1 and scope 2 definition.	LSEG Eikon
CSR Strategy Score (CSR)	The reflection of the firm's communication practice that integrates economic, social, and environmental dimensions of decision making	LSEG Eikon
Capital Expenditures (CAPEX)	Capital expenditures are sum of equipment, software development, and intangible assets spending whose life it at least one year.	LSEG Eikon
Total Energy Use (EN)	Sum of total direct and indirect energy consumption in the premises of the firm in giga joules	LSEG Eikon
Policy Board Diversity (BDIV)	Response to 'Does the company have a policy regarding gender diversity of its board?'	LSEG Eikon
Cybersecurity Policy Disclosure (CYBER)	Response to 'Does the company have a policy on cyber security in place to protect them from cyber-attacks, unauthorized access, and data leaks etc.?'	LSEG Eikon
Research and Development Expenditures (R&D)	Research and development expenditure on total revenue	LSEG Eikon
Resource Use Score (RES)	It shows the company's performance and capacity to reduce use of materials, energy and water in order to find eco-efficient alternatives	LSEG Eikon
Waste Recycling to Waste (WASTE)	Ratio of total recycled and reused waste to the total waste produced.	LSEG Eikon
Profitability (EBIT)	A gauge of corporate earnings based on broker estimate annual average	LSEG Eikon
Size of the firm (SIZE)	Log of net sales of the firm.	LSEG Eikon

$$lEN_{it} = \alpha_{10} + \alpha_{11} lCAPEX_{it} + \alpha_{12} CYBER_{it} + \alpha_{13} RND_{it} + \alpha_{14} BDIV_{it} + \alpha_{15} EBIT_{it} + \alpha_{16} SIZE_{it} + \sum_{j}^{n} \beta_{1j} Country_{it} + \sum_{k}^{m} \delta_{1k} Sector_{it} + \varepsilon_{1it} \quad (2)$$

$$CSR_{it} = \alpha_{20} + \alpha_{21} lCAPEX_{it} + \alpha_{22} CYBER_{it} + \alpha_{23} RND_{it} + \alpha_{26} BDIV_{it} + \alpha_{27} EBIT_{it} + \alpha_{28} SIZE_{it} + \sum_{j}^{n} \beta_{2j} Country_{it} + \sum_{k}^{m} \delta_{2k} Sector_{it} + \varepsilon_{2it} \quad (3)$$

$$RES_{it} = \alpha_{30} + \alpha_{31} lCAPEX_{it} + \alpha_{32} CYBER_{it} + \alpha_{33} RND_{it} + \alpha_{34} BDIV_{it} + \alpha_{35} EBIT_{it} + \alpha_{36} SIZE_{it} + \sum_{j}^{n} \beta_{3j} Country_{it} + \sum_{k}^{m} \delta_{3k} Sector_{it} + \varepsilon_{3it} \quad (4)$$

$$WASTE_{it} = \alpha_{40} + \alpha_{41} lCAPEX_{it} + \alpha_{42} CYBER_{it} + \alpha_{43} RND_{it} + \alpha_{44} BDIV_{it} + \alpha_{45} EBIT_{it} + \alpha_{46} SIZE_{it} + \sum_{j}^{n} \beta_{4j} Country_{it} + \sum_{k}^{m} \delta_{4k} Sector_{it} + \varepsilon_{4it} \quad (5)$$

These equations are also estimated using random forest whose model is estimated as follows. Where $T_b(.)$ provides prediction from bth regress trees. X_{it} is set of independent variables and Θ_b is the bootstrap sample and random feature used to growth tree b and B are number of used trees. This model is nonparametric and has ability to capture non-linearities automatically.

$$\widehat{Y_{it}} = \frac{1}{B} \sum_{b=1}^{B} T_b(X_{it}, \Theta_b) \quad (6)$$

3.3. Econometric methods

Since the data is changing across firms and time periods, estimating the two-dimension varying data using simple regression would lead to unobserved heterogeneity. This study has ventured into panel data estimation methods which can address this issue. Within panel data, estimation models like fixed and random effect models are commonly used for data which does not have long time periods calling it static panel data models. Furthermore, with expectations that the data is collected from a wide range of countries, the generalized model would lead to issues like heteroskedasticity and autocorrelation. To address this, this study has used the panel feasible generalized least squares (FGLS) method to estimate the effects of selected independent variables on the dependent variable in equations (1)–(5). This method is proposed by Greene (2003) and provides efficient estimates by altering error structure to account for autocorrelation and heteroskedasticity (Parks, 1967). Reed and Ye (2011) state that FGLS provides reliable and robust estimates in unbalanced panel data. As mentioned by Chen et al. (2016), FGLS provides asymptotically efficient estimates compared to ordinary least squares (OLS). Empirically several studies have used FGLS model in the domain of environmental economics in the panel data (Hanif et al., 2020; Hassan et al., 2019). While this model is robust to autocorrelation and heteroskedasticity, multicollinearity is checked using variance inflation factor (VIF).

Further this study has used a random forest model which as an ensemble learning method that can assess the importance of the independent variable so that the most important independent variable can be found. While regression provides the marginal effects, this model helps in showing the importances after accounting for non-linearity and complexity of interactions in the data (Breiman, 2001; Strobl et al., 2008). This method can help to find the relative importances which is not possible under the use of collinear variables in the regression method. The robust rankings, complemented with the marginal effects, can assist policy makers to prioritize policy development (Chen, 2021).

For sensitivity and robustness of the model against assumptions, this study has estimated the model using the Panel Driscoll and Kraay regression which is a 2nd generation model and robust to cross sectional dependence (Driscoll and Kraay, 1998) in the appendix since cross sectional dependence is a common issue when there are many cross sections changing across time whereby multiple factors may influence them simultaneously. Ignoring this issue may lead to unreliable results.

4. Results and discussions

Table 2 provides the descriptive statistics of the variables included in the model. It can be seen here that except for R&D all the variables have mean values higher than their standard deviation. This indicates that they are under dispersed variables within the sample while R&D is over dispersed variables. The presence of under dispersed variables in the majority shows that the selected variables follow a homogenous pattern across the companies thus relating them in one estimation equation is a suitable option. Further the non-equality of skewness to zero and kurtosis to 3 indicate that the variables are non-normal in nature; this study has availed the central limit theorem to assume that the variables are asymptotically normal (Lind et al., 2022). Moreover, since all the data is generated from the same financial statement of a firm, it is likely that there is multicollinearity. This study has included the variance inflation factor (VIF) test for the independent variables; since none of them is above 10, this rules out the chances for multicollinearity (Gujarati, 2009).

Fig. 3 presents the time evolution of the dependent variables selected for the study. These plots show the annual average of the variables and plotted using line chart. Here it can be seen that the trajectory of CO_2 emissions, CSR strategy score, and energy use are moving toward targets but for the case of resource and waste recycling it requires realignment.

Fig. 4 provides the correlation between the independent (digitization) and dependent (environmental performance) variables. Here it is noted that CYBER and R&D are negatively correlated with lCO2 and lEN while it is positively correlated with CSR, WASTE, and RES. In this sense

Table 2
Descriptive statistics.

Stats	lCO2	lEN	CSR	WASTE	RES	lCAPEX	BETA	R&D	lEBIT	BDIV	CYBER	SIZE
Mean	11.55	14.17	42.10	0.59	45.02	15.62	1.00	1495.21	17.26	0.87	0.65	18.36
Std.	2.95	2.86	33.15	0.30	33.39	3.19	0.89	32,330.1	2.71	0.33	0.48	3.35
Skewness	−0.28	−0.32	0.10	−0.43	0.03	−0.62	0.29	37.46	−0.13	−2.21	−0.62	−0.59
Kurtosis	3.05	3.99	1.60	1.98	1.62	1.39	15.49	1533.6	2.82	5.92	1.39	3.66
VIF						5.33	1.09	1.03	6.39	1.09	1.10	8.21

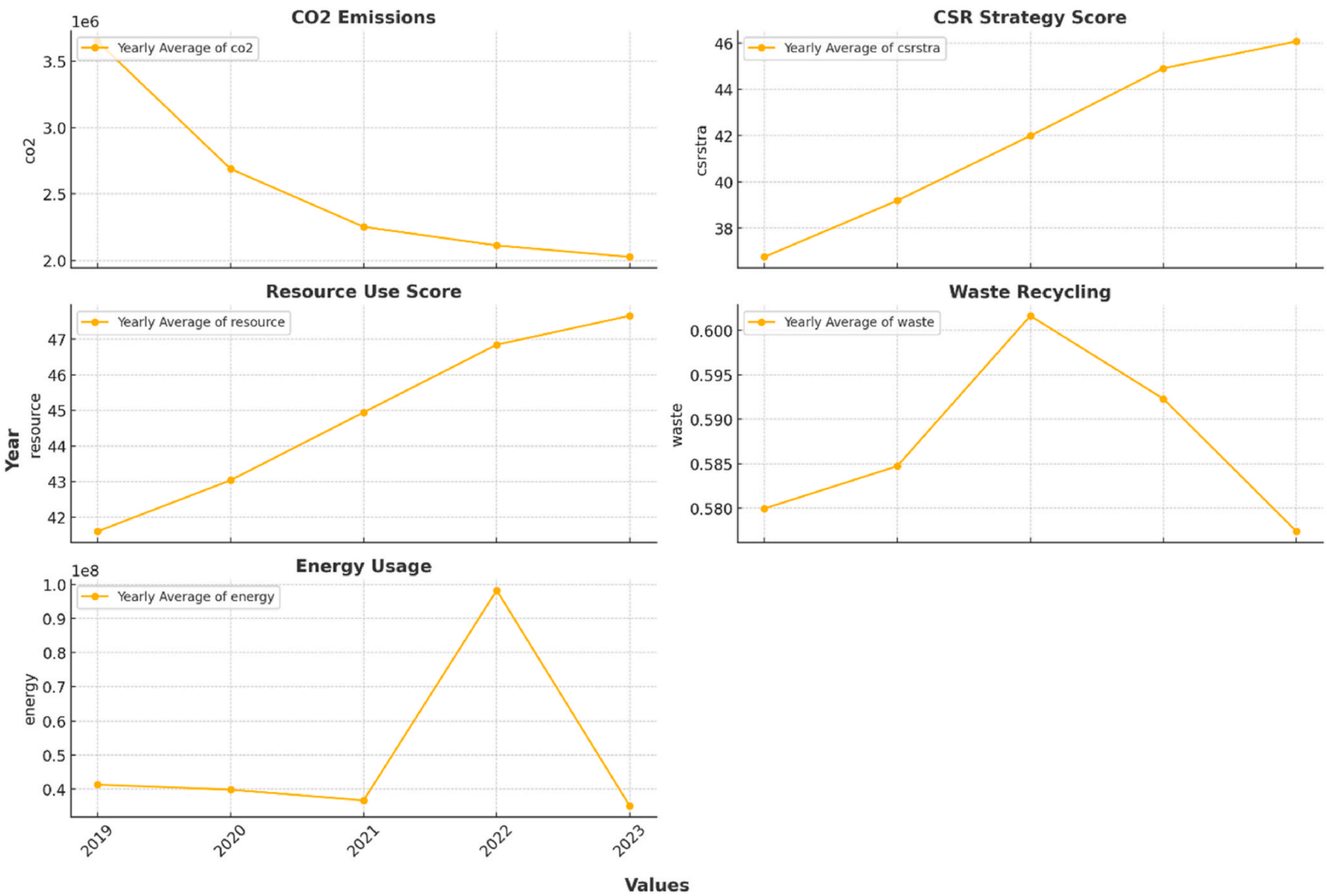

Fig. 3. – Time averages of environmental indicators.
Source: Self Constructed

both indicators are useful for the environment except for the fact that it has positive association with energy use. If the businesses offset this by moving towards renewable energy, then these two indicators are improving environmental performance. On the other hand, lCAPEX only has a favorable correlation with CSR while it is detrimental for the environment. This shows that capital expenditures deteriorate the environment during the stage when the firms are strategically spending to develop the digital infrastructure.

Table 3 provides the estimation results for equations (1)–(5). For all these models the Wald test is significant showing that the overall model is fit. The overall sample size and number of companies included in the sample are shown for each dependent variable which is mentioned in the first row. The intensity of the independent variables is visualized in Fig. 5. It shows that, for the case of CSR as dependent variable, most of the independent variables are helping it increase to improve environment while for the case of RES variable most of the variables are increasing it to deteriorate the environment.

While exploring the role of size of the firm, it has a significant effect in increasing carbon emissions, energy use, and resource use but it has also increased the waste recycling in the international businesses. Firm size had a complicated relationship with environmental outcomes (P Q. Xu et al., 2023). According to the scale effect theory, larger firms have larger production volumes which can have an effect on increase in absolute levels of carbon emissions as suggested by the studies of Cole et al. (2013) and Dinda (2004). Larger firms also use higher resources which is understood via Resource-Based-View (RBV) and organizational ecology perspectives. These firms are more resource intensive spread across an international market (Berrone et al., 2017; Hart and Dowell, 2011). Larger firms have also shown higher waste recycling rates which is aligned with the institutional theory whereby these forms face greater institutional pressures for environmental responsibility and because of their economies of scale they can implement recycling programs (King and Lenox, 2002) because of their superior resource capability (Aragón-Correa et al., 2016). Porter and Van der Linde (1995) stated that larger firms have higher capability, they use more resources but have the ability to implement sophisticated environmental management systems to become competitive in the industry.

For the case of profitability, it has a significant effect on decreasing carbon emissions, energy use, and waste recycling but it has increased CSR strategy score and resource use. The resource efficiency and Porter

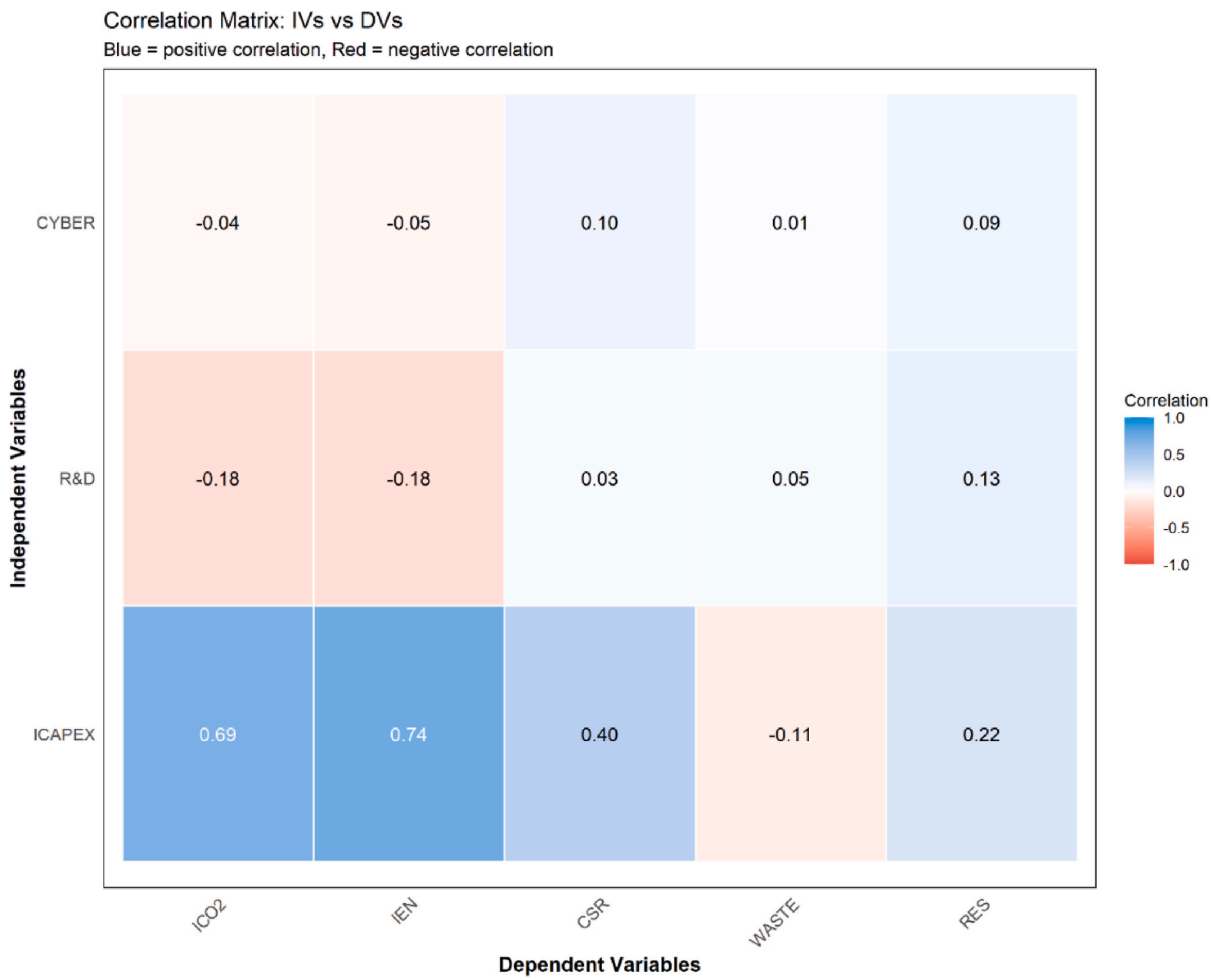

Fig. 4. – Association between variables.
Source: Self Constructed

hypothesis explain the negative effect of profits on carbon emissions. Hereby profitable firms possess the financial capacity to invest in cleaner technology and energy efficient processes (Palmer, 2017). It also aligns with the pay to be green hypothesis by Ambec and Lanoie (2008). The results of higher profits' negative effect on waste recycling are counterintuitive but it aligns with the organizational slack theory. According to it, profitable firms face less pressure to salvage value from used resources as they can afford new resources. Thus these firms consider recycling as a cost rather than an environmental initiative (Melnyk et al., 2003). There is a positive relationship between profitability and CSR strategy scores. This is explainable using stakeholder theory. Profitable firms have higher discretionary resources to invest in CSR initiatives because of demand from their stakeholders. This outcome is also discussed by Tang et al. (2012) and Williams and Siegel (2001). The expansion hypothesis, or RBV, explains how profitable firms demand more resources. These firms reinvest their earnings to growth opportunities requiring higher resources (Bansal, 2005). Broadly, one size profitable firms tend to invest in environmental improvements but they require higher resources to avail business expansion. This behavior can be further explored in corporate environmental performance at firm level (Trumpp and Guenther, 2015).

For the case of market risk, it has a significant effect on increasing carbon emissions and energy use but it has also reduced the CSR strategy score. Risks are expected to increase emissions and energy use under the risk management theory and organizational behavior under uncertainty. Risky firms often prioritize short-term survival and financial stability over environmental considerations. This relationship is also confirmed by Berrone and Gomes-Mejia (2009) and Sharfman and Fernando (2008). The theory of operational inflexibility and the resource dependence theory also explain the market risk and higher energy use. This is because risky firms tend to hold excess capacity as a buffer against volatility and prioritize operational reliability against energy efficiency (Marcus and Fremeth, 2009). The negative effect of risks on CSR strategy is aligned with slack resources theory within which risky firms reduce discretionary spending allocated for CSR initiatives. This outcome aligns with Jo and Na (2012) and Orlitzky and Benjamin (2001). Overall, this outcome shows a link between risk management and environmental stewardship where risky firms adopt conservative stance and prioritize financial stability which tends to reduce commitment for environment and society.

For the case of board diversity, having diverse boards leads to a significant increase in CSR score and resource use while it has decreased carbon emissions, energy use, and waste recycling. The positive relationship of board diversity and CSR score is aligned with resource dependence and stakeholder theory. The diversity in boards brings new perspectives, experiences, and network connections that can help firms to meet stakeholder demands (Bear et al., 2010; Post et al., 2011). Furthermore, board diversity reduces emissions under upper echelons theory and cognitive diversity perspectives. Diverse boards are engaged in more comprehensive decision making processes which are likely to

Table 3
– FGLS Estimates of Digitization model.

Variables	lCO2	lEN	CSR	RES	WASTE
lCAPEX	0.44	0.64	4.45	4.38	−0.04
	(0.00)*	(0.00)*	(0.00)*	(0.00)*	(0.01)†
CYBER	−0.10	−0.10	9.58	7.29	0.05
	(0.02)†	(0.01)†	(0.00)*	(0.00)*	(0.00)*
BDIV	−0.30	−0.005	6.56	12.55	−0.13
	(0.00)*	(0.91)	(0.00)*	(0.00)*	(0.00)*
R&D	−0.05	−0.03	−0.12	−0.27	0.001
	(0.00)*	(0.00)*	(0.07)	(0.00)*	(0.75)
BETA	0.50	0.40	−2.99	−0.22	−0.01
	(0.00)*	(0.00)*	(0.00)*	(0.76)	(0.56)
lEBIT	−0.08	−0.19	4.79	2.33	−0.01
	(0.00)*	(0.00)*	(0.00)*	(0.00)*	(0.01)†
SIZE	0.76	0.77	0.75	3.88	0.08
	(0.00)*	(0.00)*	(0.35)	(0.00)*	(0.00)*
NATION					
Austria	−0.46	−0.002	37.88	31.60	–
	(0.00)*	(0.99)	(0.00)*	(0.00)*	
Belgium	0.94	0.65	9.71	17.79	–
	(0.00)*	(0.00)*	(0.00)*	(0.00)*	
Bermuda	−0.18	0.30	7.36	20.34	−0.14
	(0.83)	(0.53)	(0.41)	(0.00)*	(0.02)
Canada	−0.98	−0.70	1.92	15.63	−0.27
	(0.00)*	(0.00)*	(0.45)	(0.00)*	(0.00)*
Denmark	−0.78	−0.03	5.63	16.59	0.01
	(0.00)*	(0.86)	(0.00)*	(0.00)*	(0.95)
Finland	0.82	1.13	46.12	35.19	−0.06
	(0.00)*	(0.00)*	(0.00)*	(0.00)*	(0.48)
France	−0.67	−0.26	−5.21	23.65	−0.16
	(0.00)*	(0.08)‡	(0.06)‡	(0.00)*	(0.04)†
Germany	−0.57	−0.11	13.74	23.54	−0.20
	(0.00)*	(0.45)	(0.00)*	(0.00)*	(0.01)†
Gibraltar	–	–	–	–	–
Greece	0.07	0.86	27.63	28.14	0.20
	(0.66)	(0.00)*	(0.00)*	(0.00)*	(0.03)†
Hungary	0.54	0.94	−11.64	−5.67	−0.12
	(0.00)*	(0.00)*	(0.10)	(0.05)‡	(0.15)
Ireland	0.03	0.20	−23.94	17.55	−0.05
	(0.83)	(0.31)	(0.00)*	(0.00)*	(0.48)
Italy	−1.09	−1.64	−27.79	30.37	−0.22
	(0.00)*	(0.00)*	(0.00)*	(0.00)*	(0.02)†
Netherlands	−2.80	−1.47	−4.09	25.37	0.14
	(0.00)*	(0.00)*	(0.57)	(0.01)†	(0.06)‡
New Zealand	−2.85	−3.24	−31.14	28.74	−0.17
	(0.00)*	(0.00)*	(0.00)*	(0.00)*	(0.07)‡
Norway	−1.06	−0.55	−0.0001	−13.77	0.35
	(0.00)*	(0.01)†	(0.99)	(0.15)	(0.00)*
Poland	−0.88	0.01	−24.95	13.52	0.07
	(0.00)*	(0.96)	(0.00)*	(0.00)*	(0.44)
Russia	0.06	−0.03	−16.77	3.44	0.47
	(0.72)	(0.88)	(0.05)‡	(0.61)	(0.00)*
Spain	−1.15	−0.48	−21.15	7.53	0.12
	(0.00)*	(0.00)*	(0.00)*	(0.17)	(0.13)
Sweden	−0.57	−0.07	12.96	32.44	−0.12
	(0.00)*	(0.62)	(0.00)*	(0.00)*	(0.12)
Switzerland	−2.33	−1.42	21.42	51.55	0.29
	(0.00)*	(0.00)*	(0.00)*	(0.00)*	(0.00)*
UK	−1.06	−0.53	21.96	14.32	−0.15
	(0.00)*	(0.00)*	(0.00)*	(0.00)*	(0.04)†
USA	−0.23	−0.19	−5.34	6.84	−0.12
	(0.03)†	(0.15)	(0.00)*	(0.00)*	(0.07)
SECTOR					
Consumer Cyclicals	−2.00	−1.89	−25.24	−7.75	0.53
	(0.00)*	(0.00)*	(0.00)*	(0.00)*	(0.00)*
Consumer non-Cyclicals	−1.09	−1.20	9.73	13.24	0.34
	(0.00)*	(0.00)*	(0.00)*	(0.00)*	(0.00)*
Energy	0.02	−0.41	−5.31	−8.55	0.05
	(0.87)	(0.00)*	(0.03)	(0.00)*	(0.31)
Healthcare	−1.744	−2.07	−22.50	−2.29	0.35
	(0.00)*	(0.00)*	(0.00)*	(0.26)	(0.00)*
Industrials	−2.14	−1.94	−12.81	−0.87	0.45
	(0.00)*	(0.00)*	(0.00)*	(0.65)	(0.00)*
Technology	−2.31	−2.40	−18.64	−11.89	0.36
	(0.00)*	(0.00)*	(0.00)*	(0.00)*	(0.00)*
Const.	−9.94	−9.54	−138.98	−180.15	−0.18
	(0.00)*	(0.00)*	(0.00)*	(0.00)*	(0.36)
Obs.	582	533	810	810	328
Groups	156	143	209	209	91
Wald (Prob.)	34,723	92,265	12,328	24,381	6161
	(0.00)*	(0.00)*	(0.00)*	(0.00)*	(0.00)*

Legend: slope coefficients are provided while the probability values are in parentheses. * Significance at 1 %, † significant at 5 %, ‡ significant at 10 %.
Source: Self Constructed

outweigh environmental outcomes (Galbreath, 2018; Glass et al., 2015). Innovation theory explains the increase in resource use because of diverse boards. This diversity promotes innovative and expansive business strategies that lead to an increase in R&D intensity resource demand (Miller and Triana, 2009). One of the surprising results is the negative effect of board diversity on the waste recycling rate. This can be explained via organizational attention theory whereby it depends on the board's priorities then focuses on broader strategic environmental goals (Hafsi and Turgut, 2013). These outcomes are aligned with broader corporate governance literature while considering unexpected outcomes with some environmental parameters.

While discussing the indicators for digital transformation, capital expenditures are discussed first. An increase in capital expenditure leads to an increase in carbon emissions, energy use, CSR score, and resource use and it decreases waste recycling. Capital expenditures are a critical component of digital transformation as it has complex relationship with environmental indicators. According to shared value theory, changes in the capital investment may lead to emissions and energy use from changes in the infrastructure (Porter and Kramer, 2011). Melville (2010) states that the digital transformation is usually energy intensive. Additionally, stakeholder theory explains the positive link between capital expenditures and CSR scores whereby digital infrastructure investments may follow corporate commitments for long term sustainability (Freeman and Reed, 1983; Luo, 2024). Hart (1995) linked it with natural resource based review to explain the role of capital expenditures lead to increase in resource demand.

The outcome of negative effect of capital expenditures is counterintuitive but it can be linked with organizational change theory. With the increase in digital transformation there would be less production of recyclable goods which will temporarily deprioritize the recycling initiative which is discussed under punctuated equilibrium model (Romanelli and Tushman, 1994) and there is a short term trade-off between operational changes and environmental performance. The outcomes show the complex relationship between capital expenditures and environmental performance which is discussed as innovator's dilemma in the domain of sustainability whereby short term environmental deterioration may be observed in response of the transformation process (Christensen, 2006).

For the case of Research and Development expenditures, it leads to decrease in carbon emissions, energy use, and resource use but it also decreases the CSR score. There are several established frameworks that can explain the role of R&D. From evolutionary economics theory, R&D drives innovation which improves efficiency leading to decreased emissions, energy use, and resource use (Nelson and Winter 1982). Moreover, the Porter hypothesis can also explain this outcome (Porter and van der Linde, 1995). Mol and Spaargaren (2000) used the ecological modernization theory to explain the link between R&D and emissions that forms eco-innovations (Kemp and Pearson, 2007). The connection with resource use is further explained using RBV and circular economy theory in forming efficient resource cycles (Geissdoerfer et al., 2017a, 2017b). Corresponding to above expected outcomes, the link between R&D and CSR scores is a paradox. According to the enlightened stakeholder theory perspective by (Jensen, 2002), technological innovation processes may reduce the focus of businesses from the social

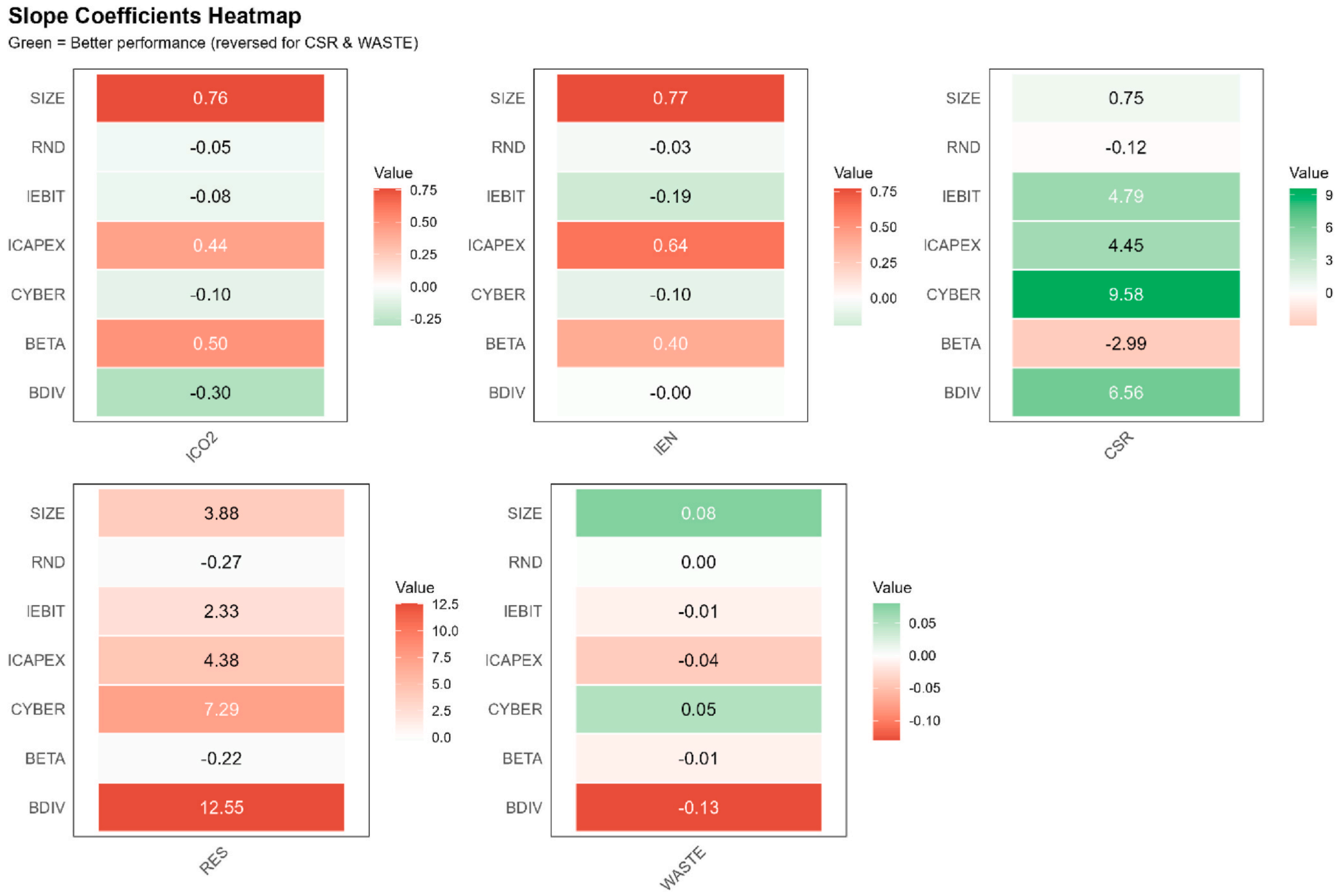

Fig. 5. – Visualized marginal effects.
Source: Self Constructed

initiatives in order to concentrate resources on technical transition. During the transition process firms may prioritize the economic and legal responsibilities rather than social ones under the CSR pyramid perspective (Carroll, 1991).

For the case of Cybersecurity disclosure, it leads to decrease in carbon emissions and energy use, but it increases the CSR score, resource use, and waste recycling rate. Suchman (1995) used the legitimacy theory to explain the positive effect of firms commitment via cybersecurity disclosure on the CSR scores. It can be explained further by using the signaling theory (Spence, 1973) where robust cybersecurity disclosure signals maturity and responsible governance of the firm. The disclosure is preceded by the implementation of digital systems which typically have a lower energy footprint. This reduces emissions based on energy efficiency hypothesis (Shrivastava, 1995) which advocate that technological governance leads to better environmental performance. This advancement also leads to an increase in resource and energy use like additional hardware and backup systems that are energy intensive, as discussed under resource dependency theory (Pfeffer and Salancik, 2003) and natural resource based view (Hart, 1995). However, this increased disclosure increases the recycling rates whereby digital transformation improves the asset management under organizational learning theory (Argote and Miron-Spektor, 2011). The improved waste management is because of improved governance for better performance leading to increased dynamic capabilities (Teece, 2007).

While the dummies for countries and sectors present the other/excluded variable effect which corresponds to that country and sector on the respective dependent variable, the significant dummy shows the significant difference from the baseline trait (country or sector) and vice versa. Here it can be noted that size of intercept value represents how that sector or country is contributing to the increase in dependent variable as an aggregate effect of all other excluded variables. While comparing the results with Table 4 in appendix (which had used Driscoll and Kraay panel data model), for all the variables which are significant there is no case where it had opposite magnitude. Thus, a cross-sectional robust model confirmed that the estimates are robust in terms of their sign across different assumptions. Note that some dummy variable coefficients are empty in Table 3 and 4 which show that they were dropped because of collinearity with any other variable.

Fig. 6 presents the machine learning based random forest model to estimate the relative importances of the digitization variables against CSR score, carbon emissions, energy use, resource use, and waste recycling. These relative importances are different from slope coefficients and provide an indicator to assess how important this variable was in forecasting the dependent variable. This is helpful in prioritizing the digitization transformation policy while considering all environmental outcomes. It can be seen here that, in most cases, the lCAPEX had shown to be most effective is creating a change in the dependent variable while other than the waste recycling model where R&D is most effective, it is second in other models. Cybersecurity disclosure has shown least importance; it has a high value for the case of waste recycling but still ranked 3rd. The results show that the hardware, software, and digital infrastructure modernization efforts had the highest yield in environmental returns. This indicates that there must be a two-tiered approach whereby infrastructure development should be prioritized and then maintain the R&D investments. The relative importance of cyber security disclosure can be further explored by using an appropriate data which is not binomial in nature. Lastly, Figs. 7, 8, and 9 show the incidence level of digitization indicators at country level. This points towards the fact that there is room for improvement in digitization space which can further improve the environmental performance of the firms.

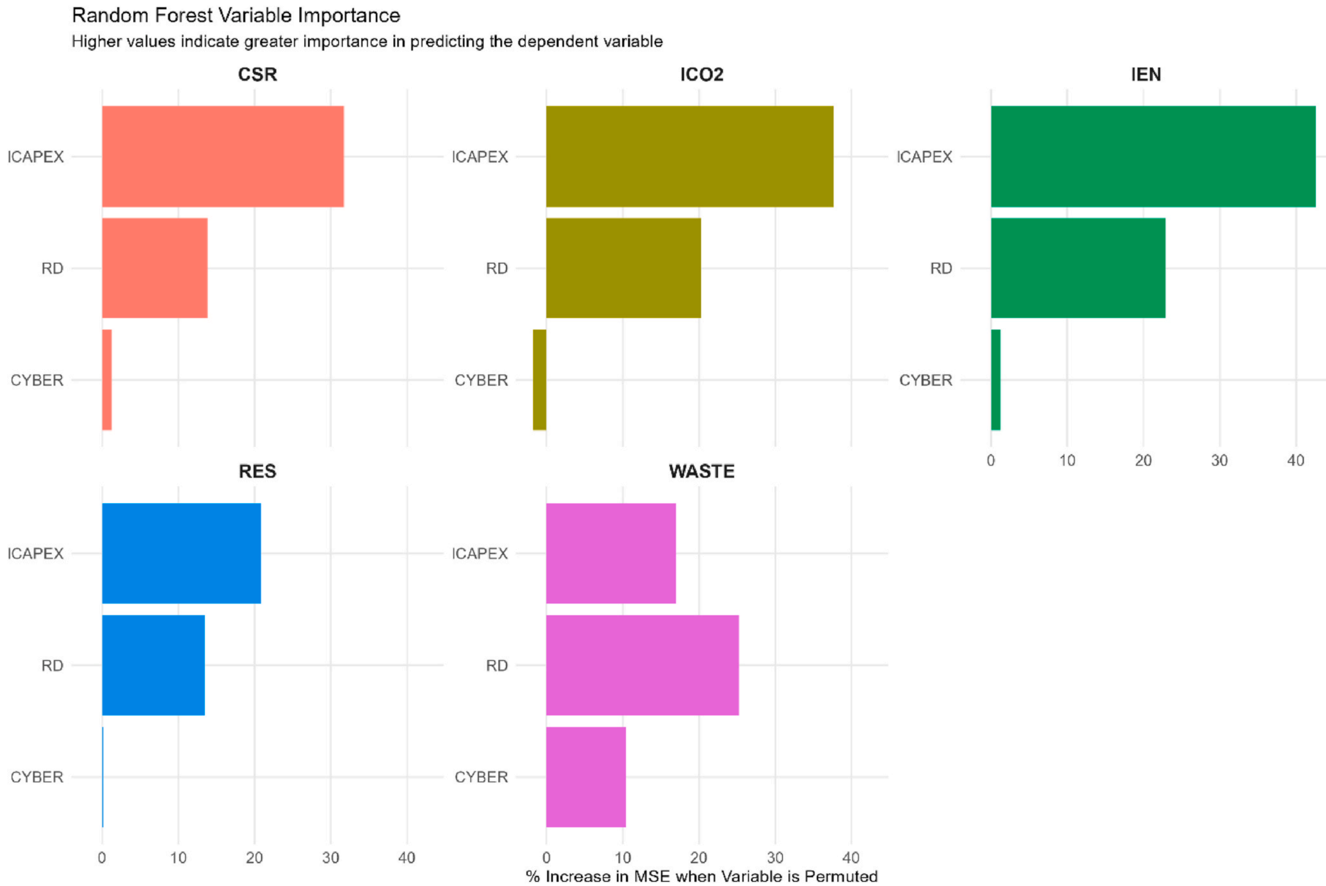

Fig. 6. – Relative importances of digitization policy instruments using random forest model.
Source: Self Constructed

5. Conclusion and policy implications

Exploring the implications of digital transformation wholistically in international businesses is the need of time. Many businesses are transforming their operational activities by adapting to digital landscape. In the profitability context there are several studies that have shown that digitalization has led to increased operational efficiency, cost reduction, and competitive advantages but the work is still in progress regarding how digitization goes beyond the first layer of business performance to social and environmental performance. The literature has coined a debate regarding the role of digitization on sustainability; on one side it can increase energy use surveillance and efficiency which can lead to sustainability (under stakeholder theory) while, on the other side, digitization can be energy intensive and can lead to an increase in growth led emissions because of scale effect (also discussed under shared value theory). To settle this debate, this study has used multiple indicators of digitization and sustainability at firm level. The diversity of the indicators helps to see how, in the longer term, digitization can ensure sustainability and what its form is.

The assessment of cross continent sample of international firms between digital transformation and environmental performance led to several conclusions. The study had used three indicators of digital transformation and maturity against five indicators which had environmental implications. This study applied the panel FGLS model including the country and sector level dummies to account for unobserved heterogeneity while this model is already robust to heteroskedasticity and autocorrelation And, for robustness, the Panel Driscoll and Kraay regression which is robust to cross sectional dependence. Since there are three indicators of digital transformation used, the challenge is to find the order of the strategy to optimize the resource utilization. This study has used the random forest model which provides relative importance estimates as compared to slope estimates of regression for each dependent variable to assist the development of policy.

The results using Panel FGLS model led to several complications in the relationship that led to the conclusion that the relationship is not linear. Firstly, capital expenditure showed a tradeoff between environmental performance and technological advancement. It led to increased emissions and resource use while it demonstrated long term sustainability. Secondly, R&D has a higher immediate positive environmental impact but at the cost of social initiatives of the firm. Thirdly, cybersecurity disclosure showed the most promising results. It indicated higher governance and transparency that led to environmental performance enhancement through lower emissions and better waste management (Achuthan et al., 2025; Hunt, 2025; Morales-Sáenz et al., 2024). The nonlinearity is observed from the fact that the digitization indicators had a negative effect on some of the environmental performance indicators that are resource oriented while they had a positive effect on other indicators which shows long-term environmental performance. The results of the FGLS and Driscoll and Kraay model are similar in terms of coefficient signs and significance showing that the changes in the model assumptions do not significantly alter the model outcomes. Further, the outcomes of the random forest model showed that the digital restructuring of the firm using capital spending is the most effective strategy across all the environmental indicators except for the waste recycling rate. The strategic R&D was the second most important strategy and it has more effectiveness for the waste recycling outcome. It is understandable that waste recycling requires more innovation than restructuring. Lastly the CSR strategy score showed low importance in all models. This points towards the need for developing a more enriched indicator that assesses the CSR commitment of the businesses. A mere binomial indicator cannot compete with other continuous indicators in the random forest model.

5.1. Policy implications

The policy implications of the panel data analysis are multifaceted. The first level is the theoretical implications. This study provided the quantitative linkage between digitization and sustainability of the firms. This assessment verified the theoretical notion that digitization can help firms achieve sustainability. This study integrated several theories which explain the multi-indicator digitization role on sustainability. Empirically, this study starts with the need for policymakers to implement appropriate regulatory frameworks that tries to minimize the short-term environmental impacts of digital transformation. Further, governments should incentivize R&D investments in clean and efficient digital solutions to increase immediate positive impact on environment. Similarly, cybersecurity measures should be made compulsory as an integral part of environmental, social, and governance (ESG) reporting frameworks. ESG disclosures must also add more detail in the cybersecurity disclosure from binomial to multinomial so that its effect can be further explored.

Businesses should be persuaded to adopt a balanced approach to digital transformation which can mitigate the short- and long-term environmental effects. The transition plans must offset the environmental impact across all dimensions. Each country and sector should have their own policy framework adjustments that can help firms to optimize their digital transition while sustaining environmental performance.

5.2. Research limitations and future directions

The outcomes of the study are limited to the sample and using the estimation method. The study explored the Global North as a major driver of energy demand and emissions so its outcomes cannot directly be applied for the Global South other than understanding the best practices. The data structure does not allow the assessment of dynamic behaviors. This study did not account for the spillover effects of increase in the adoption of digital technology available and access to recent technologies. Certainly, different sectors could gain differently from digitization as compared to others. Future studies can explore more dimensions of environmental performance in other businesses in a longer time frame to assess the temporal behavioral patterns. Furthermore, studies could also venture into the firms' organizational culture differences and the role of different evolving technologies and their cross-integration in forming environmental outcomes. A sub sample analysis along with controlling potential endogeneity can help further extend the outcomes of the study.

CRediT authorship contribution statement

Marco De Sisto: Writing – review & editing, Writing – original draft, Project administration, Conceptualization. **Shajara Ul-Durar:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Conceptualization. **Noman Arshed:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Ashina Sadaf:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Alireza Nazarian:** Writing – review & editing, Writing – original draft, Validation.

Informed consent

No consent was required as secondary data has been used in this study.

Declaration of competing interest

All the authors hereby state that there is no conflict of interest with the content of this article, both in terms of academic and professional capacity. It is to affirm that the work is not submitted anywhere else other than this journal.

Ethical approval

The entire research process is in line with our institutional research ethics policies. We declare that all ethical standards are met and complied with in true letter and spirit.

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Declaration of competing interest

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

Appendix

Table 4
Sensitivity analysis using 2nd Generation panel data model.

Variable	lCO2	lEN	CSR	RES	WASTE
lCAPEX	0.554**	0.723***	4.260	3.948	−0.065
CYBER	0.068	−0.017	12.022**	9.393***	0.0815*
BDIV	−0.456*	0.048	5.960**	12.984**	−0.142***
R&D	−0.042*	−0.025*	−0.179**	−0.249*	0.004
BETA	0.593**	0.509***	−2.318**	−0.687	−0.031
lEBIT	−0.082	−0.237*	5.901***	2.468**	−0.016
SIZE	0.670***	0.721***	−0.782	3.794	0.089
NATION					
Austria	−0.613*	−0.335*	33.751***	29.854**	(empty)
Belgium	0.610*	0.383**	9.129*	15.787**	(empty)
Bermuda	0.381	0.395	1.711	21.408***	−0.196
Canada	−1.901**	−1.449*	−2.808	13.252*	−0.246*
Denmark	−1.277***	−0.568**	2.594	17.654*	−0.138

(continued on next page)

Table 4 (*continued*)

Variable	lCO2	lEN	CSR	RES	WASTE
Finland	0.962*	0.995*	30.486**	33.823*	−0.153
France	−0.794*	−0.613***	−9.019	26.252**	−0.171
Germany	−0.724*	−0.362	13.595*	22.197*	−0.181
Gibraltar	−0.788*	(empty)	16.247***	−7.176	(empty)
Greece	0.181	1.214**	27.877**	28.626*	0.111
Hungary	0.481	0.717*	−13.906	−5.327	−0.158
Ireland	−0.050	−0.009	−21.153**	12.214**	0.007
Italy	−1.339***	−1.859***	−28.509***	31.609**	−0.218
Netherlands	−4.759***	−2.792**	−15.653*	2.481	0.097
New Zealand	−3.382***	−3.797***	−35.169***	25.320*	−0.234
Norway	−1.198***	−0.349	−1.141	−13.682**	0.318*
Poland	−0.780	−0.138	−21.905**	12.453	−0.050
Russia	0.176	0.254	−16.828	9.295	0.456**
Spain	−1.306**	−0.697**	−26.272***	6.732	0.061
Sweden	−0.592*	−0.081	8.996	29.096***	−0.118
Switzerland	−2.639***	−1.383**	17.874**	41.946**	0.132*
UK	−1.050**	−0.894***	16.666**	12.454	−0.084
US	−0.415*	−0.447**	−8.758	5.719	−0.147
SECTOR					
Consumer Cyclicals	−2.022***	−1.681***	−18.375***	−8.280**	0.424***
Consumer non-Cyclicals	−0.936***	−1.013**	11.273***	12.085**	0.220***
Energy	−0.165	−0.786**	−3.167	−9.161	0.044
Healthcare	−1.768***	−2.072***	−18.840**	−3.628	0.295*
Industrials	−2.140***	−1.884***	−9.318**	−2.182	0.297***
Technology	−2.123***	−2.429***	−15.024***	−11.691***	0.277*
_cons	−10.153***	−9.239**	−125.099**	−171.907***	0.201102
N	582	533	810	810	328

Legend: *p < .05; **p < .01; ***p < .001.
Source: Self Constructed.

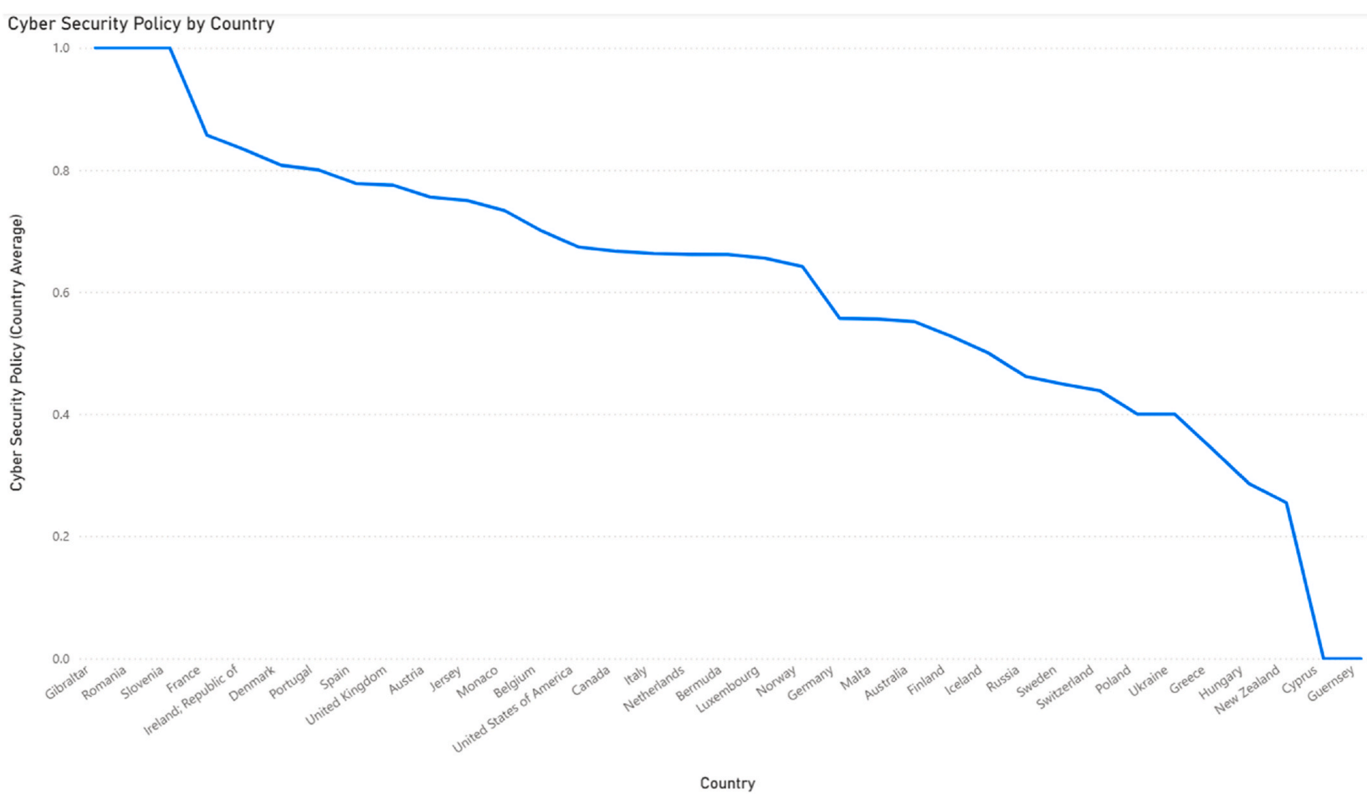

Fig. 7. Cyber Security Policy Disclosure Average by Country.
Source: Self Constructed

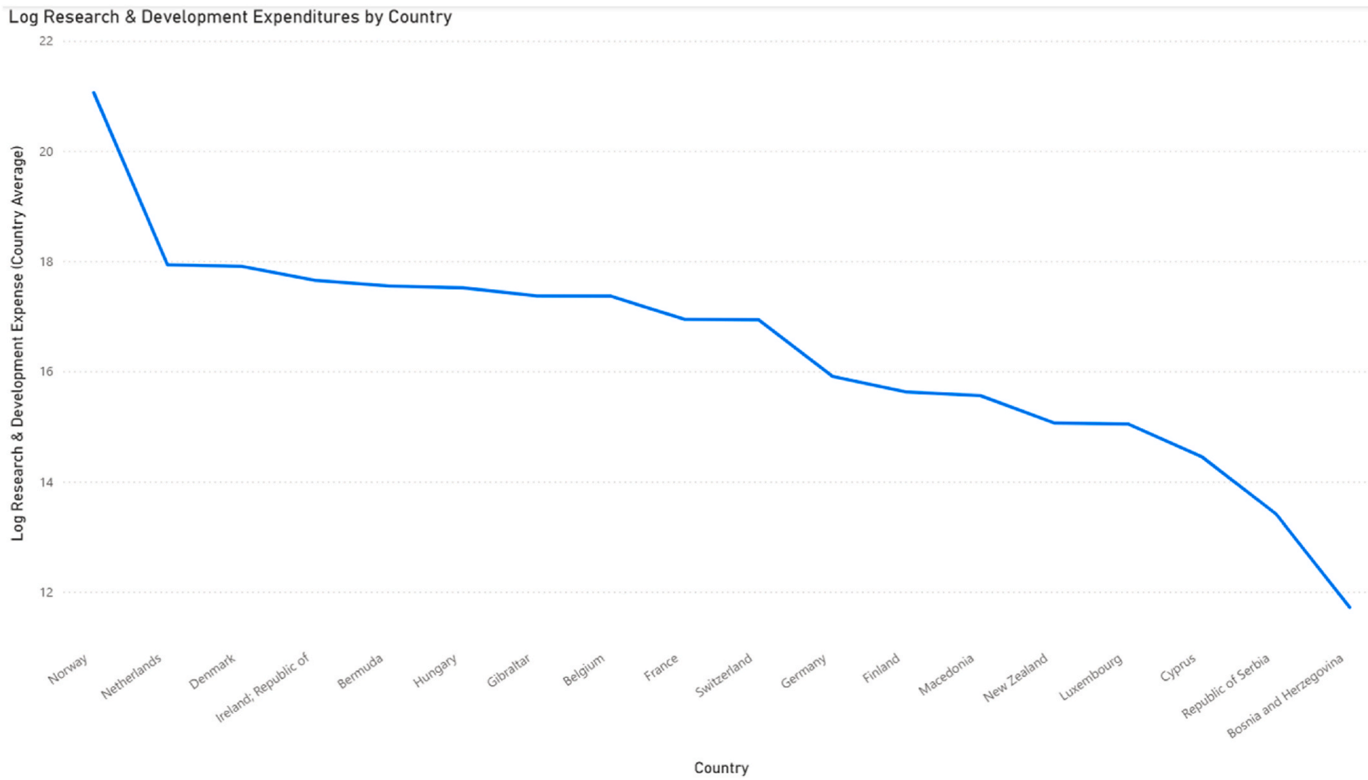

Fig. 8. Research and Development Expenditures Average by Country.
Source: Self Constructed

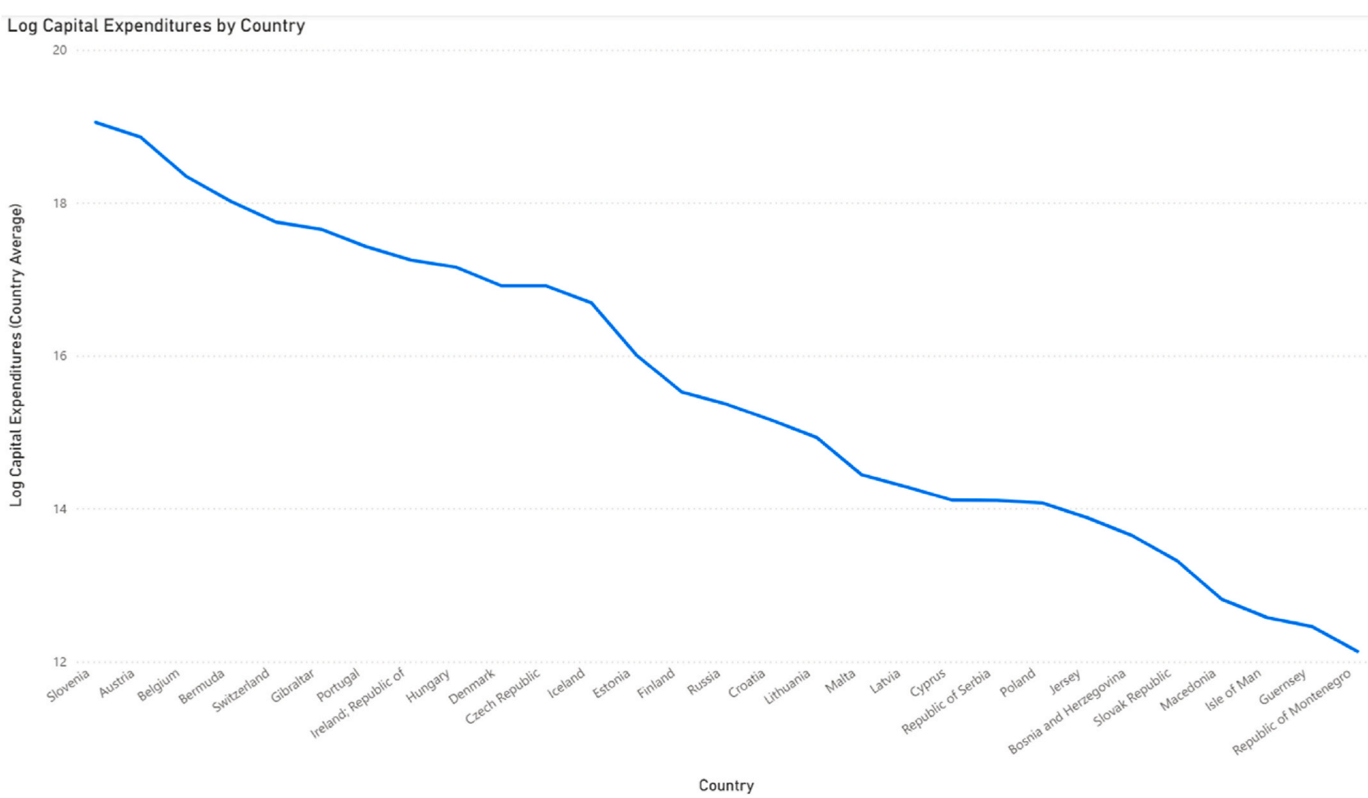

Fig. 9. Capital Expenditures Average by Country.
Source: Self Constructed

Data availability

Data will be made available on request.

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