



Research article

Green innovation and corporate decarbonization: The moderating role of sustainable governance in Euronext-listed companies

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Abstract: Achieving net-zero emissions requires not only technological innovation but also effective governance mechanisms that can support and enhance corporate sustainability initiatives. While prior studies have examined the individual effects of green innovation and governance practices on environmental performance, limited evidence exists regarding their combined influence on corporate carbon emissions. This study investigated the relationship between green innovation, sustainable governance, and carbon emissions among Euronext-listed firms. Using a panel dataset of 304 companies covering the period 2017–2023, the study employed OLS regression models with industry and year fixed effects and conducted two-step system GMM estimation as a robustness test. The study examined the effects of green innovation and sustainable governance on total, direct (Scope 1), and indirect (Scope 2) carbon emissions while accounting for firm-specific characteristics and potential endogeneity concerns. The results revealed a significant negative association between green innovation and corporate carbon emissions, indicating that firms with stronger green innovation performance tend to exhibit lower levels of total, direct, and indirect emissions. Furthermore, the interaction between green innovation and sustainable governance is negative and statistically significant, suggesting that sustainable governance is associated with a stronger emissions-reducing effect of green innovation. These findings provide evidence that green innovation and sustainable governance function as complementary organizational capabilities that contribute to corporate decarbonization. The study contributes to the sustainable finance and corporate sustainability literature by highlighting the importance of integrating innovation strategies with governance

mechanisms to improve environmental performance and accelerate progress toward net-zero objectives. The findings offer practical implications for corporate managers, investors, and policymakers seeking effective pathways to support long-term sustainability and climate-related goals.

Keywords: green innovation; sustainable governance; carbon emissions; corporate decarbonization; sustainable finance; net-zero transition

JEL Codes: M14, G30, Q56

1. Introduction

Climate change has become one of the most pressing global challenges, prompting governments, corporations, and investors to accelerate efforts toward achieving net-zero emissions. International climate initiatives and increasingly stringent environmental policies have strengthened pressure on firms to reduce greenhouse gas emissions while maintaining economic competitiveness (Cohen et al., 2022; Keerthana et al., 2023). Corporations play an important role in this transition because their operational activities and energy consumption contribute substantially to global carbon emissions. Consequently, environmental performance has become an increasingly important consideration for regulators, investors, consumers, and other stakeholders. Among the strategies available to firms, green innovation has emerged as an important mechanism for improving environmental performance. Green innovation includes environmentally oriented products, technologies, processes, and managerial practices that promote cleaner production, energy efficiency, resource conservation, and pollution reduction (Alsmadi & Al-Omouh, 2025; Valdivieso-Uvidia et al., 2025; Keerthana et al., 2024). Prior research has shown that environmental and technological innovation can contribute to lower carbon emissions through cleaner production systems, renewable energy adoption, and more efficient resource utilization (Han et al., 2025; Töbelmann & Wendler, 2020; Mongo et al., 2021).

European studies have similarly demonstrated the importance of innovation-related activities for environmental performance. Therefore, the contribution of the present study is not based on establishing green innovation as a completely new determinant of emissions, but on examining the organizational conditions under which its environmental benefits may be strengthened. One such organizational condition is sustainable governance. Governance mechanisms such as sustainability-focused board oversight, executive remuneration linked to sustainability objectives, sustainability reporting, and external assurance can support the implementation, monitoring, and accountability of environmental initiatives (Hartikainen et al., 2021; Gerwing et al., 2022). Green innovation may provide firms with technologies and processes capable of improving environmental performance, but the realization of these benefits may depend on whether appropriate governance structures support their implementation (Albitar et al., 2023). From this perspective, green innovation and sustainable governance may operate as complementary organizational capabilities rather than independent drivers of environmental performance. Stakeholder and investor expectations have also become increasingly important, as ESG-oriented investment strategies expand, and multi-stakeholder approaches gain prominence in sustainability-related decision-making (Tanaka & Tanaka, 2022). In the European context, sustainability-related regulation and the growing importance of green finance have further increased

investor attention to environmental performance and sustainability-oriented investments (Grumann et al., 2024). This relationship is particularly relevant for Euronext-listed firms, which operate within a European institutional environment characterized by strong climate policies, sustainability disclosure requirements, and increasing stakeholder expectations (Nicolò et al., 2022).

Although previous research (Qureshi et al., 2022) has examined environmental innovation and carbon emissions in Europe, much of the evidence has focused on country-level relationships, patent-based indicators, or the independent effects of innovation and governance. Comparatively less attention has been given to firm-level evidence on whether sustainability-oriented governance strengthens the association between green innovation and corporate emissions across different emission categories. Accordingly, this study examines the relationship between green innovation, sustainable governance, and corporate carbon emissions among 304 Euronext-listed firms during 2017–2023. The analysis evaluates total emissions as well as direct (Scope 1) and indirect (Scope 2) emissions using OLS models with industry and year fixed effects, complemented by two-step system GMM estimation. The study contributes to the existing literature by providing firm-level European evidence on the green innovation–emissions relationship, examining sustainable governance as a moderating organizational condition, and distinguishing between total, direct, and indirect emissions. In doing so, the study provides a more specific understanding of how innovation and governance are jointly associated with corporate decarbonization.

The remainder of the paper is organized as follows. Section 2 develops the theoretical framework and hypotheses. Section 3 describes the data and methodology. Section 4 presents the variables and their definitions. Section 5 outlines the econometric models. Section 6 reports the empirical results and robustness analyses. Section 7 discusses the findings, and Section 8 concludes the study.

2. Theoretical framework and hypothesis development

2.1. Conceptual foundations

2.1.1. Green innovation

Green innovation refers to the development, adoption, and implementation of environmentally oriented products, technologies, processes, and managerial practices designed to reduce environmental impacts while improving organizational efficiency and competitiveness (Takalo et al., 2021; Khanra et al., 2022). Unlike conventional innovation, which primarily focuses on economic and operational performance, green innovation explicitly incorporates environmental objectives by promoting cleaner production, energy efficiency, resource conservation, waste minimization, and pollution reduction (Sun et al., 2023; Chen et al., 2024). As environmental concerns become increasingly integrated into corporate strategy, green innovation has emerged as an important mechanism through which firms can achieve both sustainability and long-term value creation (Khanra et al., 2022).

2.1.2. Sustainable governance

Sustainable governance refers to the organizational structures, oversight mechanisms, accountability systems, and managerial processes that integrate sustainability objectives into corporate decision-making. It encompasses sustainability-focused board committees, executive

remuneration linked to sustainability objectives, sustainability reporting practices, and external assurance mechanisms that promote transparency, accountability, and strategic oversight. Unlike ESG performance, which reflects observable sustainability outcomes, sustainable governance represents the internal governance mechanisms that guide, monitor, and support the implementation of sustainability-related initiatives (Opoku et al., 2026). Consequently, sustainable governance provides the institutional foundation through which firms can effectively pursue environmental and social objectives.

2.1.3. Corporate carbon emissions

Carbon emissions represent one of the most important indicators of corporate environmental performance and climate-related impact. Corporate emissions arise from both direct operational activities and indirect energy consumption. As regulators, investors, and stakeholders increasingly emphasize climate-related risks and net-zero commitments, reducing carbon emissions has become a central objective of corporate sustainability strategies. Consequently, carbon emissions provide an appropriate measure for evaluating the environmental effectiveness of firms' innovation activities and governance practices.

2.2. *Green innovation and corporate carbon emissions*

The relationship between green innovation and environmental performance has received considerable attention in sustainability, environmental economics, and corporate governance research. Green innovation enables firms to develop cleaner technologies, improve energy efficiency, optimize resource utilization, and reduce environmental impacts associated with production processes. Through these mechanisms, firms can lower carbon emissions while simultaneously improving operational performance and maintaining competitiveness. Previous studies report a significant negative relationship between environmental innovation and carbon emissions across various industries and economic contexts (Du et al., 2019; Töbelmann & Wendler, 2020; Mongo et al., 2021). Environmentally oriented innovations facilitate cleaner production systems, renewable energy integration, energy-efficient operations, and waste-minimization strategies that contribute to lower carbon intensity. Moreover, green innovation enables firms to respond proactively to environmental regulations and increased stakeholder expectations regarding sustainability performance. From a strategic perspective, green innovation represents an organizational capability that supports both environmental and economic objectives. Investments in environmentally friendly technologies can reduce environmental risks, improve resource efficiency, and create opportunities for sustainable growth. Consequently, firms exhibiting stronger green innovation capabilities are expected to achieve superior environmental outcomes, including lower levels of carbon emissions.

Accordingly, the following hypothesis is proposed:

H1: Green innovation is negatively associated with corporate CO₂ emissions.

2.3. *Sustainable governance as a moderating mechanism*

Although green innovation provides firms with technologies, processes, and capabilities that can improve environmental performance, these benefits may not automatically translate into

measurable reductions in corporate emissions. Their effectiveness can depend on the organizational and governance conditions that support implementation, monitoring, and managerial commitment. Prior research suggests that governance mechanisms improve sustainability performance by strengthening accountability, transparency, strategic oversight, and long-term decision-making (Dyck et al., 2019; Shive & Forster, 2020). Sustainable governance can therefore enhance the effectiveness of green innovation through sustainability-focused board oversight, executive incentive alignment, sustainability reporting, and external assurance. These mechanisms help align managerial objectives with environmental goals, improve the monitoring of innovation activities, and reduce gaps between sustainability strategies and their operational implementation. From a contingency theory perspective, the effectiveness of green innovation is therefore conditional on the governance environment in which it is implemented. Firms with stronger sustainability-oriented governance structures are expected to translate environmentally oriented innovation more effectively into improved environmental outcomes and lower emissions. Accordingly, sustainable governance is conceptualized as a moderating mechanism that strengthens the negative relationship between green innovation and corporate carbon emissions.

2.4. The joint role of green innovation and sustainable governance

Green innovation and sustainable governance should not be viewed as isolated organizational capabilities. Rather, they represent complementary mechanisms supporting corporate decarbonization. Green innovation provides the technological solutions necessary to improve environmental performance, whereas sustainable governance provides the organizational infrastructure required to implement, monitor, and sustain those innovations effectively. Firms characterized by both strong innovation capabilities and robust governance structures are therefore expected to achieve greater reductions in carbon emissions than firms relying on innovation alone. This complementary relationship suggests that the environmental benefits of green innovation are amplified when supported by strong governance practices. In other words, governance enhances the effectiveness of innovation by ensuring that sustainability initiatives are embedded within organizational decision-making processes and translated into measurable environmental outcomes.

Accordingly, the following hypothesis is proposed:

H2: Sustainable governance strengthens the negative relationship between green innovation and corporate CO₂ emissions.

3. Data and methodology

3.1. Sample selection and data sources

This study examines the relationship between green innovation, sustainable governance, and corporate carbon emissions among firms listed on the Euronext stock exchange. Euronext provides an appropriate setting due to its strong emphasis on sustainability, environmental disclosure, and corporate governance practices. Firm-level financial, environmental, governance, and sustainability data were obtained from the Thomson Reuters Refinitiv Eikon database, a widely used source in sustainability and corporate governance research. The initial sample consisted of all Euronext-listed firms with available environmental and governance information during the study period. Firms with

missing observations for the primary variables were excluded to ensure consistency and comparability. The final sample comprised 304 companies, representing 2128 firm-year observations covering the period from 2017 to 2023. Industry classifications were based on the NACE (Nomenclature des Activités Économiques dans la Communauté Européenne) framework. In Europe, corporate emissions are also influenced by regulatory mechanisms such as the EU Emissions Trading System (EU ETS), while sustainability reporting requirements have been strengthened through the Corporate Sustainability Reporting Directive (CSRD). However, because the sample covers 2017–2023, the direct influence of the CSRD is limited, as its principal reporting requirements apply from the 2024 financial year onward. These institutional factors are considered when interpreting the findings and represent relevant areas for future research.

3.2. Empirical strategy

The study examines whether green innovation is associated with lower corporate carbon emissions and whether sustainable governance strengthens this relationship. OLS regression models with industry and year fixed effects are employed as the baseline estimation approach. Industry fixed effects control for sector-specific characteristics, while year fixed effects capture common temporal shocks. Huber–White robust standard errors are used to address heteroscedasticity. A set of control variables, including board quality, ESG ratings, firm size, financial leverage, profitability, liquidity, and financial distress, is incorporated to reduce omitted variable bias and improve estimation reliability.

3.3. Addressing endogeneity concerns

Potential endogeneity may arise from reverse causality, omitted variables, and unobserved firm-specific characteristics. To address these concerns, the study complements the baseline OLS analysis with a two-step system GMM estimator. The system GMM specification does not include a lagged dependent variable as a regressor. Instead, lagged values of the potentially endogenous explanatory variables are used as internal instruments in the differenced and level equations to address potential endogeneity. This approach helps mitigate simultaneity concerns and improves estimation consistency. The validity of the GMM specification is assessed using first-order autocorrelation [AR(1)], second-order autocorrelation [AR(2)], and Hansen overidentification tests. The reported results provide additional support for the robustness of the empirical findings.

Table 1. Variables and definitions.

Variable	Definitions
Year	2017, 2018, 2019, 2020, 2021, 2022, and 2023.
Industry	Industry indicators from NACE.
Total emissions	Total corporate carbon emissions measured as the sum of direct emissions (Scope 1) and indirect emissions (Scope 2), expressed in thousand metric tons of CO ₂ equivalent. Natural logarithmic transformations are used in the regression analyses.
Green innovation	The lagged innovation score of the company in the year $t-1$.
ESG committee	A binary variable equal to 1 if the firm maintains an ESG committee, and 0 otherwise.
ESG executive remuneration	A binary variable equal to 1 if executive remuneration is linked to sustainability objectives, and 0 otherwise.
ESG report	A binary variable equal to 1 if the firm publishes an ESG report, and 0 otherwise.
ESG externally assured	A binary variable equal to 1 if the firm's ESG report is externally assured, and 0 otherwise.
Sustainable governance	A governance score derived from the sum of four ESG-related binary indicators: ESG committee, ESG executive remuneration, ESG report, and ESG externally assured. The score ranges from 0 to 4.
Board executives	A binary variable equal to 1 if the board size exceeds the industry median, and 0 otherwise.
Board gatherings	A binary variable equal to 1 if the number of board meetings exceeds the industry median, and 0 otherwise.
Board equality	A binary variable equal to 1 if the female member's percentage is greater than the industry median, and 0 otherwise.
Board longevity	A binary variable equal to 1 if average board tenure exceeds the industry median, and 0 otherwise.
Board external members	A binary variable equal to 1 if the percentage of independent directors is greater than the industry median, and 0 otherwise.
Board quality	A board quality index derived from the sum of five board-related binary indicators: board executives, board gatherings, board equality, board longevity, and board external members. The score ranges from 0 to 5.
ESG ratings	ESG score obtained from the Refinitiv database, measured on a numerical scale.

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Variable	Definitions
Company's scale	Natural log of the firm's total assets in the year t.
Company's financial leverage	Firm's total debts in the year t divided by total assets ratio in the year t-1.
Company's ROA	Firm's net income in the year t divided by the average total assets in the year t-1.
Company's current ratio	Firm's current ratio in the year t.
Company's net loss	A binary variable equal to 1 if the firm has a negative net income in the year t, and 0 otherwise.

4. Variables and their definitions

This study examines the relationship between corporate carbon emissions, green innovation, sustainable governance, and firm-specific characteristics. Corporate carbon emissions serve as the dependent variable, while green innovation represents the primary explanatory variable. Sustainable governance is incorporated as a moderating variable to examine whether governance structures strengthen the emissions-reducing effect of green innovation. Additional governance and financial control variables are included to reduce omitted variable bias. Detailed variable definitions are presented in Table 1.

4.1. Dependent variable: Total emissions

Following prior research (Albitar et al., 2023; Konadu et al., 2022), corporate carbon emissions are measured as the total emissions of the firm, calculated as the sum of Scope 1 (direct emissions) and Scope 2 (indirect emissions), expressed in thousand metric tons of CO₂ equivalent. Descriptive statistics are reported using the original emission values, while natural logarithmic transformations are employed in the regression analyses to reduce skewness and improve comparability across firms.

4.2. Independent variable: Green innovation

The primary explanatory variable is green innovation, measured by the one-year-lagged Environmental Innovation Score from the Refinitiv Eikon database. The score reflects a firm's ability to reduce environmental costs and burdens for its customers and to create new market opportunities by improving existing environmental technologies and processes and by developing eco-designed products and processes. Green innovation may also be measured through environmental patent counts. However, such measures capture specific technological innovation outputs and may not reflect the broader range of environmentally oriented products, processes, and practices considered in the present study. The Environmental Innovation Score ranges from 0 to 100, with higher values indicating stronger engagement in environmentally oriented innovation activities. The one-year lag accounts for

the time required for green innovation activities to influence firms' operational processes and environmental outcomes. Accordingly, the measure captures a firm's broader environmental innovation performance, including cleaner production technologies, environmentally oriented products and processes, and resource-efficient practices, rather than relying on a single innovation indicator such as R&D expenditure or green patent counts.

4.3. Moderating variable: Sustainable governance

Sustainable governance encompasses the governance structures and accountability mechanisms that support the implementation of sustainability within firms. The index is constructed using four binary indicators: ESG committee, ESG executive remuneration, ESG report, and ESG externally assured. Each indicator takes a value of 1 when the respective governance mechanism is present and 0 otherwise. The four components are equally weighted and summed to construct the Sustainable Governance Index, resulting in a score ranging from 0 to 4. Equal weighting is adopted because each component represents a distinct sustainability-oriented governance mechanism, without assuming that any individual component is more important than the others. Higher values therefore indicate the presence of a broader set of sustainability-oriented governance mechanisms within the firm. The four components exhibit a Cronbach's α of 0.615, indicating modest internal consistency. Given that the index combines distinct governance mechanisms rather than interchangeable measures of a single governance attribute, the additive construction is retained.

4.4. Control variables

Several governance and financial control variables are included to account for alternative determinants of corporate carbon emissions. Board quality is measured using an additive index comprising five board-related indicators: board size, board meeting frequency, board gender diversity, board tenure, and board independence. Each indicator takes a value of 1 when the corresponding board characteristic exceeds the industry median and 0 otherwise. Following the index-based approach adopted in prior research, the five components are equally weighted and summed, resulting in a board quality score ranging from 0 to 5. The equal-weight approach is adopted because the components represent distinct dimensions of board governance, without assuming that any individual characteristic is more important than the others. Higher values therefore indicate the presence of a broader set of board governance characteristics. Financial control variables include the company scale (natural logarithm of total assets), financial leverage (total debt divided by total assets), return on assets (ROA), current ratio, and net loss. In addition, industry and year fixed effects based on NACE classifications are included in all empirical models to control for industry-specific and time-specific heterogeneity.

5. Econometric model specification

To examine the relationship between green innovation and corporate carbon emissions, this study employs ordinary least squares (OLS) regression models with industry and year fixed effects. Robust Huber–White standard errors are utilized to address potential heteroscedasticity concerns.

The baseline model used to test Hypothesis 1 is specified as follows:

$$\begin{aligned}
\text{Total emissions}_{i,t} &= \beta_0 + \beta_1 \text{Green Innovation}_{i,t-1} + \beta_2 \text{Sustainable Governance}_{i,t} \\
&+ \beta_3 \text{Board quality}_{i,t} + \beta_4 \text{ESG ratings}_{i,t} + \beta_5 \text{Company's scale}_{i,t} \\
&+ \beta_6 \text{Company's financial leverage}_{i,t} + \beta_7 \text{Company's ROA}_{i,t} \\
&+ \beta_8 \text{Company's Current Ratio}_{i,t} + \beta_9 \text{Company's Net Loss}_{i,t} \\
&+ \text{Industry fixed effects} + \text{Year fixed effects} + \epsilon_{i,t}
\end{aligned} \tag{1}$$

To test Hypothesis 2, an interaction term between green innovation and sustainable governance is developed. The interaction model is specified as follows:

$$\begin{aligned}
\text{Total emissions}_{i,t} &= \beta_0 + \beta_1 \text{Green Innovation}_{i,t-1} + \beta_2 \text{Sustainable Governance}_{i,t} \\
&+ \beta_3 \text{Board quality}_{i,t} + \beta_4 \text{ESG ratings}_{i,t} + \beta_5 \text{Company's scale}_{i,t} \\
&+ \beta_6 \text{Company's financial leverage}_{i,t} + \beta_7 \text{Company's ROA}_{i,t} \\
&+ \beta_8 \text{Company's Current Ratio}_{i,t} + \beta_9 \text{Company's Net Loss}_{i,t} \\
&+ \beta_{10} \text{Green Innovation}_{i,t} \times \text{Sustainable Governance}_{i,t} \\
&+ \text{Industry fixed effects} + \text{Year fixed effects} + \epsilon_{i,t}
\end{aligned} \tag{2}$$

The interaction term captures the moderating effect of sustainable governance on the relationship between green innovation and carbon emissions. A significantly negative coefficient indicates that stronger sustainable governance strengthens green innovation's emissions-reducing effect. This specification allows the study to evaluate whether firms characterized by both high levels of green innovation and strong governance structures achieve greater reductions in carbon emissions than firms relying on innovation alone. To address potential endogeneity concerns, the baseline OLS estimations are complemented with a two-step system GMM estimator. System GMM is particularly suitable for panel datasets because it controls for unobserved firm-specific effects and utilizes internal instruments derived from lagged variables. This approach helps mitigate potential biases arising from reverse causality, omitted variables, and simultaneity between green innovation, sustainable governance, and corporate emissions.

6 Results

6.1. Descriptive statistics

Table 2 presents the descriptive statistics for all variables used in the analysis. The emissions variables are reported using their original values, whereas logarithmic transformations are employed in the regression analyses. The average total emissions of Euronext-listed firms amount to 32.77, with values ranging from 15.50 to 80.90, indicating substantial variation in firms' environmental footprints. The mean values for direct and indirect emissions are 26.64 and 5.17, respectively, suggesting that direct operational emissions constitute the largest component of overall corporate emissions. Green innovation exhibits a mean value of 35.45 and ranges from 2.40 to 92.10, indicating considerable variation in firms' sustainability-oriented innovation activities. Sustainable governance reports a mean value of 2.91 and ranges from 0 to 4, suggesting that most firms maintain relatively strong sustainability-oriented governance structures. The average board quality score is 2.98 out of a maximum value of 5, while the mean ESG rating is 58.83, reflecting a moderate to high level of sustainability performance across the sample. Regarding financial characteristics, the average firm size is 22.22, the mean financial leverage

ratio is 0.29, and the average ROA is 13.40. The mean current ratio of 1.56 indicates adequate liquidity, while the net loss variable reports a mean value of 0.02, suggesting that only a small proportion of observations experienced negative earnings during the study period.

Table 2. Descriptive statistics.

Variables	Min.	Max.	Mean	SD	Variance	Skewness	Kurtosis
Total emissions	15.50	80.90	32.77	13.09	171.27	1.08	0.88
Direct emissions	15.10	79.10	26.64	11.53	132.84	1.52	2.97
Indirect emissions	0.10	10.90	5.17	2.56	6.56	0.17	−0.18
Green innovation	2.40	92.10	35.45	28.77	827.92	0.85	−0.61
Sustainable governance	0	4	2.91	0.37	0.13	−4.33	1.41
Board quality	0	5	2.98	1.44	2.083	0	−1.2
ESG ratings	0.70	92.10	58.83	19.79	391.50	−0.59	−0.21
Company's scale	14	28	22.22	2.12	4.51	−0.01	0.60
Company's financial leverage	0.01	0.95	0.29	0.16	0.03	0.58	0.57
Company's ROA	0.40	35.20	13.40	8.96	80.30	0.50	−0.84
Company's current ratio	0.20	8.20	1.56	1.04	1.08	2.65	1.14
Company's net loss	0.00	1	0.02	0.14	0.02	6.94	1.47

Note: Emissions variables (total emissions, direct emissions, and indirect emissions) are reported in their original units (thousand metric tons of CO₂ equivalent). Log-transformed values are used in the regression analyses.

6.2. Correlation analysis

Table 3 presents the Pearson correlations among the study variables. Total emissions are strongly correlated with direct emissions ($r = 0.96$, $p < 0.01$) and positively correlated with indirect emissions ($r = 0.37$, $p < 0.01$), as expected given their compositional relationship. Green innovation is negatively associated with total emissions ($r = -0.09$, $p < 0.01$) and direct emissions ($r = -0.06$, $p < 0.01$), providing preliminary evidence that greater environmental innovation is associated with lower emissions. Sustainable governance ($r = -0.04$, $p < 0.10$) and ESG ratings ($r = -0.06$, $p < 0.01$) also show negative associations with total emissions, whereas board quality exhibits a weak and insignificant relationship. Among the control variables, company scale and financial leverage show weak and statistically insignificant correlations with total emissions, while ROA is positively associated with total emissions ($r = 0.13$, $p < 0.01$), and the current ratio shows a weak negative association ($r = -0.04$, $p < 0.10$). The highest correlations among the explanatory variables are observed between company scale and ROA ($r = 0.69$, $p < 0.01$) and between ESG ratings and company scale ($r = 0.66$, $p < 0.01$). As all pairwise correlations remain below 0.80, the results do not indicate

severe multicollinearity concerns. The relatively weak bivariate correlation between green innovation and total emissions should not be directly compared with the higher R^2 values of the multivariate models. Pearson correlations capture unconditional pairwise associations, whereas the regression models account jointly for governance measures, firm characteristics, and industry and year fixed effects. Thus, the higher R^2 reflects the combined explanatory contribution of the full model rather than green innovation alone.

Table 3. Pearson correlation matrix.

Variables	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
(I) Total emissions	1											
(II) Direct emissions	0.96***	1										
(III) Indirect emissions	0.37***	0.15***	1									
(IV) Green innovation	−0.09***	−0.06***	0.15***	1								
(V) Board quality	−0.034	−0.05**	0.06***	0.07***	1							
(VI) Sustainable governance	−0.04*	0.14***	0.09***	0.039*	0.07***	1						
(VII) ESG ratings	−0.06***	−0.06***	−0.02	0.23***	0.56***	0.06***	1					
(VIII) Company's scale	0.03	0.02	0.02	0.24***	0.44***	−0.05**	0.66***	1				
(IX) Company's financial leverage	−0.01	−0.007	−0.03	−0.01	0.001	0.021	0.03	−0.15***	1			
(X) Company's ROA	0.13***	−0.04*	0.15***	0.22***	−0.02	0.18***	−0.03	0.69***	0.01	1		
(XI) Company's current ratio	−0.04*	−0.06***	−0.03	−0.13***	−0.05**	−0.15***	−0.21***	−0.07***	0.02	−0.09***	1	
(XII) Company's net loss	−0.015	0.03	0.03	0.02	0.01	−0.03	0.03	−0.12***	−0.11***	0.19***	0.09***	1

Note: This table reports Pearson correlation coefficients among the study variables. Total emissions represent the sum of Scope 1 (direct emissions) and Scope 2 (indirect emissions) and are reported in their original units (thousand metric tons of CO₂ equivalent). *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

6.3. Green innovation and corporate carbon emissions

Table 4 reports the baseline regression results examining the relationship between green innovation and corporate carbon emissions. Model 1 uses total emissions as the dependent variable, Model 2 examines direct emissions, and Model 3 focuses on indirect emissions. Industry and year fixed effects are included in all specifications, and robust standard errors are employed. The coefficient of green innovation is negative and statistically significant across all three models. Specifically, green innovation is negatively associated with total emissions ($\beta = -0.99$, $p < 0.05$), direct emissions ($\beta = -0.05$, $p < 0.10$), and indirect emissions ($\beta = -0.002$, $p < 0.05$). These findings indicate that firms exhibiting stronger sustainability-oriented innovation activities tend to report lower carbon emissions, supporting Hypothesis 1. The results are consistent with prior studies suggesting that environmentally oriented innovation contributes to cleaner production processes, improved resource efficiency, and reduced environmental impacts. Among the governance variables, sustainable governance exhibits a negative and statistically significant relationship with emissions across all specifications, suggesting that firms characterized by stronger sustainability-oriented governance structures tend to achieve lower levels of carbon emissions. ESG ratings and board quality also display negative coefficients, indicating that stronger governance and sustainability performance are associated with improved environmental outcomes. Regarding firm-specific characteristics, company scale and financial leverage are positively associated with emissions, whereas ROA and current ratio exhibit negative relationships. These findings suggest that larger and more highly leveraged firms tend to generate higher emissions, while financially efficient and liquid firms are better positioned to support sustainability initiatives and environmental management practices. The explanatory power of the models is substantial, with R^2 values of 0.83, 0.65, and 0.62 for total, direct, and indirect emissions, respectively. The results provide strong evidence that green innovation is associated with lower corporate carbon emissions and represents an important organizational capability supporting corporate decarbonization.

Table 4. Baseline regression results: Green innovation and corporate carbon emissions.

Variables	Model 1	Model 2	Model 3
Constant variables	Total emissions	Direct emissions	Indirect emissions
Constant	−9.26 (0.000)***	−12.32 (0.003)***	−9.19 (0.002)***
Green innovation	−0.99 (0.018)**	−0.05 (0.056)*	−0.002 (0.022)**
Board quality	−0.45 (0.031)**	−0.22 (0.063)*	−0.36 (0.076)*
Sustainable governance	−0.38 (0.003)***	−0.25 (0.009)***	−0.68 (0.003)***
ESG ratings	−0.25 (0.079)*	−0.06 (0.095)*	−0.14 (0.034)**
Company's scale	0.26 (0.023)**	0.74 (0.008)***	0.12 (0.001)***
Company's financial leverage	0.21 (0.043)**	8.46 (0.038)**	1.83 (0.002)***
Company's ROA	−0.15 (0.027)**	−0.066 (0.003)***	−0.007 (0.001)***
Company's current ratio	−0.09 (0.003)***	−0.44 (0.043)**	−0.055 (0.096)*
Company's net loss	0.039 (0.004)***	6.58 (0.079)*	0.67 (0.022)**
Year FE	Yes	Yes	Yes

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Variables	Model 1	Model 2	Model 3
Industry FE	Yes	Yes	Yes
R ²	0.83	0.65	0.62
Observations	2128	2128	2128

Note: This table reports OLS regression results with industry and year fixed effects. Robust standard errors are reported. p-values are shown in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

6.4. Moderating role of sustainable governance

Table 5 reports the regression results examining whether sustainable governance moderates the relationship between green innovation and corporate carbon emissions. The interaction term between green innovation and sustainable governance is negative and statistically significant across all models. Specifically, the interaction coefficient is -0.087 ($p < 0.01$) for total emissions, -0.035 ($p < 0.01$) for direct emissions, and -0.041 ($p < 0.01$) for indirect emissions. These findings indicate that the emissions-reducing effect of green innovation becomes stronger as sustainable governance increases, supporting Hypothesis 2. The results suggest that firms characterized by both strong innovation capabilities and robust sustainability-oriented governance structures achieve greater reductions in carbon emissions than firms relying on innovation alone. The coefficients of green innovation and sustainable governance remain negative and statistically significant across all specifications, further confirming their roles in improving environmental performance. In addition, the inclusion of the interaction term increases the explanatory power of the models, with R² values rising to 0.84, 0.76, and 0.80 for total, direct, and indirect emissions, respectively. Figure 1 illustrates the moderating effect of sustainable governance on the relationship between green innovation and total emissions. The negative association between green innovation and emissions becomes stronger at higher levels of sustainable governance, consistent with the significant interaction effects reported in Table 5.

Table 5. Moderating effect of sustainable governance on the relationship between green innovation and corporate carbon emissions.

Variables	Model 1	Model 2	Model 3
Constant variables	Total emissions	Direct emissions	Indirect emissions
Constant	−14.5 (0.003)***	−14.2 (0.002)***	−8.84 (0.002)***
Green innovation	−2.06 (0.036) **	−4.29 (0.063) *	−1.31 (0.024) **
Board quality	−0.16 (0.083) *	−0.26 (0.033) **	−0.37 (0.072) *
Sustainable governance	−0.18 (0.042) **	−0.24 (0.029) **	−0.47 (0.044) **
ESG ratings	−0.39 (0.035) **	−0.48 (0.042) **	−0.14 (0.006) ***
Company's scale	0.016 (0.093) *	0.028 (0.093) *	0.12 (0.078) *
Company's financial leverage	5.24 (0.006) ***	4.12 (0.037)**	2.84 (0.033) **
Company's ROA	−0.008 (0.032) **	−0.046 (0.019) **	−0.06 (0.059) *

Continued on next page

Variables	Model 1	Model 2	Model 3
Company's current ratio	−0.007 (0.020) **	−0.014 (0.043) **	−0.56 (0.099) *
Company's net loss	0.014 (0.091) *	0.080 (0.078) *	0.621 (0.083) *
Green innovation × sustainable governance	−0.087 (0.002) ***	−0.035 (0.001) ***	−0.041 (0.003) ***
Year FE	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
R ²	0.84	0.76	0.80
Observations	2,128	2,128	2,128

Note: This table reports OLS regression results with industry and year fixed effects. Robust standard errors are reported, and p-values are shown in parentheses. Models 1–3 use total emissions, direct emissions, and indirect emissions as dependent variables, respectively. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

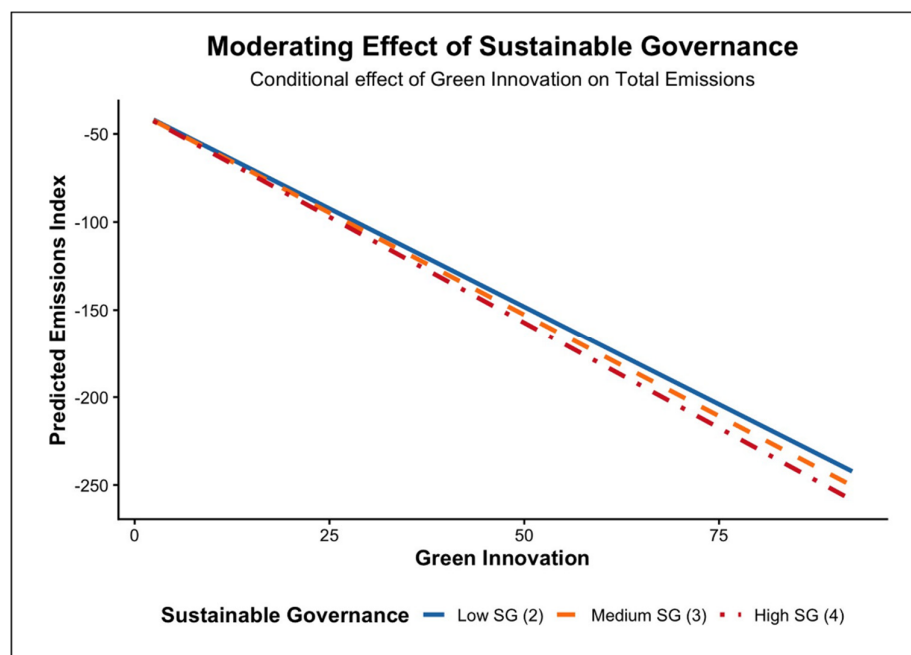


Figure 1. Moderating effect of sustainable governance on the relationship between green innovation and total emissions.

6.5. ESG-based subsample analysis

Table 6 presents the subsample analysis in which firms are separated according to whether their ESG ratings are above or below the sample mean. Green innovation remains negatively and significantly associated with carbon emissions in both groups. However, the coefficient is larger for firms with above-average ESG ratings ($\beta = -9.08$, $p < 0.05$) than for firms with below-average ESG ratings ($\beta = -5.05$, $p < 0.05$), suggesting that firms with stronger sustainability performance derive greater environmental benefits from innovation activities. Sustainable governance also exhibits a negative and significant relationship with emissions across both subsamples, indicating that

sustainability-oriented governance structures contribute to lower emissions regardless of ESG-performance level. The results further suggest that the environmental benefits of green innovation and governance are more pronounced among firms exhibiting stronger ESG performance. The explanatory power of the models remains high, with R^2 values of 0.94 and 0.85 for firms with ESG ratings above and below the sample mean, respectively. These findings provide additional evidence that innovation, governance, and ESG-oriented practices jointly support corporate decarbonization.

Table 6. ESG-based subsample analysis of green innovation, sustainable governance, and corporate carbon emissions.

Variables	ESG > mean	ESG < mean
Constant	−21.9 (0.003) ***	−21.5 (0.001) ***
Green innovation	−9.08 (0.038) **	−5.05 (0.024) **
Sustainable governance	−4.36 (0.091) *	−2.15 (0.032) **
Board quality	−3.18 (0.003) ***	−2.18 (0.043) **
ESG ratings	−4.15 (0.023) **	−1.02 (0.082) *
Company's scale	1.52 (0.072) *	1.17 (0.008) ***
Company's financial leverage	1.32 (0.052) *	1.16 (0.046) **
Company's ROA	−1.16 (0.044) **	−1.10 (0.025) **
Company's current ratio	−2.01 (0.007) ***	−2.09 (0.003) ***
Company's net loss	0.41 (0.042) **	0.14 (0.043) **
Year FE	Yes	Yes
Industry FE	Yes	Yes
R^2	0.94	0.85
Observations	1130	998

Note: This table reports OLS regression results for firms with ESG ratings above and below the sample mean. Industry and year fixed effects are included in all models. Robust standard errors are reported, and p-values are shown in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

6.6. Subsample analysis based on sustainable governance

Table 7 presents the subsample analysis based on sustainable governance. Firms are classified as above or below the sample mean for sustainable governance scores. Green innovation remains negatively and significantly associated with carbon emissions in both groups. However, the coefficient is larger for firms with above-average governance scores ($\beta = -3.70$, $p < 0.05$) than for firms with below-average governance scores ($\beta = -2.20$, $p < 0.05$), suggesting that stronger governance structures enhance the environmental benefits of innovation activities. Sustainable governance and board quality also exhibit significant negative relationships with emissions in both subsamples. ESG ratings remain negatively associated with emissions, with stronger effects observed among firms

exhibiting higher governance quality. These findings suggest that governance structures and sustainability performance complement innovation efforts in supporting corporate decarbonization. The explanatory power of the models remains relatively high, with R^2 values of 0.79 and 0.71 for firms with governance scores above and below the sample mean, respectively. The results provide additional evidence that stronger governance structures enhance the effectiveness of green innovation in reducing corporate carbon emissions.

Table 7. Sustainable governance-based subsample analysis of green innovation and corporate carbon emissions.

Variables	Governance > mean	Governance < mean
Constant	−1.29 (0.008)***	−0.48 (0.002)***
Green innovation	−3.7 (0.023)**	−2.2 (0.017)**
Sustainable governance	−0.18 (0.045)**	−0.07 (0.028)**
Board quality	−1.34 (0.031)**	−0.94 (0.043)**
ESG ratings	−4.22 (0.093)*	−1.2 (0.086)*
Company's scale	0.92 (0.030)**	0.23 (0.019)**
Company's financial leverage	0.57 (0.092)*	0.22 (0.083)*
Company's ROA	−4.22 (0.007)***	−1.43 (0.053)*
Company's current ratio	−1.99 (0.042)**	−0.94 (0.094)*
Company's net loss	3.2 (0.007)***	1.2 (0.032)**
Year FE	Yes	Yes
Industry FE	Yes	Yes
R^2	0.79	0.71
Observations	1,366	762

Note: This table reports OLS regression results for firms with sustainable governance scores above and below the sample mean. Industry and year fixed effects are included in all models. Robust standard errors are reported, and p-values are shown in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

6.7. Robustness analysis: Two-step system GMM

To address potential endogeneity concerns arising from reverse causality, omitted variables, and unobserved firm-specific heterogeneity, the baseline models are re-estimated using a two-step system GMM estimator. The results are reported in Table 8. The findings remain consistent with the baseline OLS results. Green innovation continues to exhibit a negative and statistically significant association with total emissions ($\beta = -1.45$, $p < 0.05$), direct emissions ($\beta = -0.23$, $p < 0.05$), and indirect emissions ($\beta = -0.97$, $p < 0.05$). Sustainable governance also maintains a negative and significant relationship with emissions across all specifications. Most importantly, the interaction term between green innovation and sustainable governance remains negative and highly significant across all models. The interaction

coefficients are -0.092 ($p < 0.01$), -0.061 ($p < 0.01$), and -0.074 ($p < 0.01$) for total, direct, and indirect emissions, respectively. These results provide additional support for the moderating role of sustainable governance and indicate that stronger governance structures enhance the emissions-reducing effect of green innovation. The diagnostic tests further support the validity of the system GMM specifications. The AR(1) tests are statistically significant, whereas the AR(2) tests are insignificant across all three models ($p = 0.193$, 0.534 , and 0.769), indicating no evidence of second-order serial correlation. The Hansen test p-values of 0.390 , 0.430 , and 0.220 do not reject the null hypothesis of instrument validity. In addition, the number of instruments used in Models 1, 2, and 3 is 39, 46, and 52, respectively, which remain well below the number of firms (304), reducing concerns regarding instrument proliferation. The consistency of the OLS and system GMM estimates, together with the diagnostic results, provides additional evidence that the reported associations are robust to potential endogeneity concerns.

Table 8. Robustness analysis using two-step system GMM estimation.

Variables	Model 1	Model 2	Model 3
Constant variables	Total emissions	Direct emissions	Indirect emissions
Constant	-16.2 (0.004)***	-10.92 (0.002)***	-2.73 (0.009)***
Green innovation	-1.45 (0.013)**	-0.23 (0.044)**	-0.97 (0.014)**
Sustainable governance	-2.93 (0.042)**	-1.25 (0.033)**	-0.83 (0.032)**
Board quality	-1.32 (0.052)*	-0.71 (0.052)*	-0.92 (0.042)**
ESG ratings	-2.12 (0.004)***	-1.63 (0.033)**	-1.33 (0.093)*
Company's scale	3.2 (0.002)***	2.2 (0.043)**	1.55 (0.053)*
Company's financial leverage	7.2 (0.023)**	3.2 (0.043)**	1.13 (0.026)**
Company's ROA	-0.82 (0.084)*	-0.21 (0.058)*	-0.19 (0.043)**
Company's current ratio	-1.55 (0.024)**	-0.42 (0.037)**	-0.21 (0.087)*
Company's net loss	1.3 (0.078)*	1.01 (0.085)*	0.2 (0.073)*
Green innovation $\times$ sustainable governance	-0.092 (0.000)***	-0.061 (0.002)***	-0.074 (0.002)***
Year FE	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
R ²	0.92	0.84	0.88
AR1	0.002	0.001	0.01
AR2	0.193	0.534	0.769
Hansen test (p-value)	0.39	0.43	0.22
No. of instruments	39	46	52
No. of firms	304	304	304
Robust standard error	Yes	Yes	Yes
Observations	2021	2021	2021

Note: This table reports two-step system GMM estimates. Industry and year fixed effects are included in all models. Robust standard errors are reported, and p-values are shown in parentheses. AR(1) and AR(2) denote first- and second-order autocorrelation tests, respectively. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. The models do not include a lagged dependent variable as a regressor; lagged values of the potentially endogenous explanatory variables are used as internal instruments.

7. Discussion

This study examined the relationship between green innovation, sustainable governance, and corporate carbon emissions among Euronext-listed firms. The results indicate that green innovation is associated with lower levels of total, direct, and indirect emissions. These findings are consistent with Töbelmann and Wendler (2020) and Mongo et al. (2021), who also reported that environmental innovation contributes to lower CO₂ emissions. However, prior studies largely rely on country-level analysis or patent-based measures of innovation, whereas the present study provides firm-level evidence using the Refinitiv Environmental Innovation Score. These differences in measurement and level of analysis may partly explain variations in the magnitude of the reported effects. A key finding of this study is that sustainable governance strengthens the negative association between green innovation and corporate emissions. This suggests that governance mechanisms related to oversight, accountability, reporting, and incentive alignment may help firms translate environmentally oriented innovation into improved environmental performance. The subsample analyses and two-step system GMM results further support the robustness of these findings. As an additional robustness check, we re-estimated the baseline and interaction specifications for total emissions using firm and year fixed effects, with standard errors clustered at the firm level (Table A1). The results remain consistent with the main findings: green innovation retains a negative association with total emissions, while the interaction between green innovation and sustainable governance remains negative and statistically significant ($\beta = -0.07$, $p = 0.046$), indicating that the principal conclusions are robust to controlling for time-invariant firm-specific heterogeneity. The study extends prior research by showing that the relationship between green innovation and lower emissions is not only linked to innovation itself but also to the governance context in which it is implemented.

8. Conclusions

This study examined the relationship between green innovation, sustainable governance, and corporate carbon emissions among Euronext-listed firms during the period 2017–2023. Using a panel dataset of 304 firms and employing both OLS and two-step system GMM estimations, the study investigated whether green innovation is associated with lower emissions and whether sustainable governance strengthens this relationship. The findings indicate that green innovation is associated with lower levels of total, direct, and indirect emissions. Furthermore, the interaction between green innovation and sustainable governance is negative and statistically significant across all model specifications, suggesting that firms with stronger sustainability-oriented governance structures derive greater environmental benefits from innovation activities. These results indicate that green innovation and sustainable governance function as complementary organizational capabilities supporting corporate decarbonization. From a practical perspective, firms should complement green innovation with ESG oversight, sustainability-linked executive remuneration, ESG reporting, and external

assurance, while future research should examine these governance mechanisms separately to identify their relative moderating effects. Several limitations should be acknowledged. First, the analysis focuses exclusively on Euronext-listed firms, which may limit the generalizability of the findings. Second, the study relies on secondary sustainability and governance data that may not fully capture all dimensions of firms' environmental strategies. Third, the analysis focuses on Scope 1 and Scope 2 emissions and excludes Scope 3 emissions. This is important because value-chain emissions may represent a substantial share of the total carbon footprint in some industries. Accordingly, the findings should be interpreted as relating primarily to firms' direct operational and purchased-energy emissions rather than their complete value-chain carbon footprint. Finally, although the system GMM approach helps mitigate endogeneity concerns, the findings should be interpreted as evidence of robust associations rather than definitive causal relationships. Future research may extend this analysis to other institutional settings, incorporate Scope 3 emissions and other environmental performance indicators, and employ alternative identification strategies to further investigate the relationship between innovation, governance, and corporate decarbonization.

Author contributions

Shih-Wei Wu: Conceptualization, Supervision, Methodology, Writing – review and editing. Kokulnathan Thangavelu: Methodology, Investigation, Formal analysis, Data curation, Visualization. Keerthana K. B.: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review and editing.

Use of AI tools declaration

The authors declare that they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare that there are no conflicts of interest in this paper.

Data availability statement

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

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