Business Strategy and the Environment

WILEY | Business Strategy and the Environment

RESEARCH ARTICLE OPEN ACCESS

The Impact of Carbon Pricing on Corporate Sustainability: Evidence From the European Union

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Received: 1 July 2025 | **Revised:** 16 September 2025 | **Accepted:** 13 October 2025

Funding: The authors received no specific funding for this work.

Keywords: carbon prices | CO_2 emissions | corporate sustainability | EU-ETS | green innovation | greenhouse gas emissions

ABSTRACT

The European Union (EU) has played a leading role in the fight against climate change. One mechanism used to meet the targets for global greenhouse gas (GHG) emission reductions is carbon pricing. A prominent example is the EU Emissions Trading System (EU-ETS). This study examines the effectiveness of political decisions to pursue environmental objectives from a firm-level perspective. The aim of this research is to analyse how carbon prices affect firm-level GHG emissions and environmental innovation. We also examine the relationship between environmental innovation and corporate GHG emissions, both independently and after including the effects of carbon pricing. Our findings show that carbon prices have a negative relationship with corporate CO_2 emissions and a positive relationship with green innovation in low-carbon technologies. Our results confirm that green innovation exerts a limited impact on GHG emissions, with carbon prices acting as the main driver of corporate GHG emission reductions.

1 | Introduction

Reducing greenhouse gas (GHG) emissions is one of the biggest challenges of our time. In response to this challenge, the European Union (EU) Emissions Trading System (EU-ETS) was launched to mitigate the effects of climate change and reduce GHG emissions. As the world's first carbon market, the EU-ETS requires companies to purchase emission allowances to cover their carbon emissions (Colmer et al. 2023; Mañas-Álvarez et al. 2024).

Although these allowances were initially allocated free of charge, this free allocation is declining. The purpose of free allocation is to facilitate corporate adaptation and prevent carbon leakage (i.e., the relocation of production to countries with weaker or even no environmental regulations). The gradual reduction in free allocation forces companies to purchase emission allowances in the carbon market to cover their emission deficits (Gaztañaga et al. 2022; Mañas-Álvarez et al. 2024). This mechanism is designed to encourage companies to modernise their facilities and reduce their GHG emissions. Carbon pricing thus drives decarbonisation, embodying the principle that polluters should bear the cost of their emissions (European Commission 2024a).

Research has primarily examined the relationship between carbon prices and emission volumes at the national level, focusing on the effect of carbon pricing policies on country-level emissions. Most studies have centred on Europe, probably because the EU-ETS was the first emissions trading market and is now the largest such market (Green 2021). These studies reveal a small impact of this type of policy on national emissions. The global expansion of emissions trading markets has led to similar analyses in other countries, most notably Japan, China and South Korea. However, the results remain inconclusive, showing little impact (Arimura and Abe 2021) or even none (Wakabayashi and Kimura 2018).

In contrast, company-level evidence remains limited, despite its potential to provide important insights into how carbon allowance prices affect corporate GHG emissions. Such analysis could reveal differences across companies based on sector and company characteristics such as environmental awareness and innovation capacity. Most studies have focused on the influence of implementing the emissions trading market on emission volumes (Colmer et al. 2023; Dechezleprêtre et al. 2023). Few studies have explicitly examined the impact of carbon pricing on corporate GHG emissions (Adamolekun 2024, for the European market; Le and Azhgaliyeva 2023, for the Asian market).

The emissions trading system aims not only to make polluters pay for their GHG emissions but also to reduce their emissions while generating revenue to finance the green transition. Therefore, at the company level, a pertinent question is how much impact the implementation of these systems and emission allowance prices have on companies' environmental innovation. Studies examining the relationship between implementing emissions trading markets and innovation investment have yielded mixed results. Most have identified a positive relationship, attributed to the carbon pricing mechanism, which creates direct financial incentives for regulated firms to invest in low-carbon technologies (Calel and Dechezleprêtre 2016), and to the maturity of available low-carbon technologies at the time of implementation, which enables firms to respond with innovation rather than mere adoption (Calel 2020). Others have reported a negative relationship, which emerges when carbon trading policies create resource allocation distortions that redirect funds from innovation to regulatory compliance (Zhang et al. 2022) and when negative upstream effects reduce innovation incentives (Chen et al. 2021). Some studies have found no significant relationship, attributing this finding to low carbon prices, which fail to generate meaningful innovation incentives (Löfgren et al. 2014; Lunde 2022). This lack of unanimity motivated the present study of how corporate environmental research and development (green R&D) affects GHG emissions and what role carbon prices play in this relationship.

There is also limited research on the specific impact of carbon pricing on R&D investment. A notable exception is the study by Lin and Wesseh (2020), who showed a positive effect of CO_2 pricing on corporate R&D expenditure in the Chinese National Emissions Trading System (CN-ETS). The present research addresses this gap in the literature by analysing the effectiveness of carbon pricing in driving the business transition towards sustainable models with lower GHG emissions and cleaner technological innovation. A study of this relationship at the level of company facilities affected by emissions market regulations is necessary. Such a study is especially important for the EU-ETS, which is currently the main carbon market worldwide.

Our aim in this study is to analyse the relationships between carbon pricing, GHG emissions and environmental innovation in European companies. First, we analyse the impact of carbon pricing on corporate GHG emissions and environmental innovation. Second, we examine the relationship between environmental innovation and corporate GHG emissions, both independently and after including the effects of carbon pricing. Our study is based on an initial sample of 189,969 European company facilities regulated by the EU-ETS during the period 2008 to 2023 across 6258 companies based in the EU-27. Given data availability constraints, the final sample consists of 1967 companies. This sample provides a solid basis for examining the historical trends in EU-ETS and its impact over a broad period covering different phases.

Through this article, we contribute to the literature in several ways. First, we present a firm-level study of EU-ETS-regulated facilities, identifying firms that not only have GHG emissions but that are also required to participate in the emissions market. Second, we specifically consider carbon price as a key variable in the EU-ETS, examining its impact on companies' environmental policies (emission levels and investment in environmental innovation). In addition, we extend existing evidence by analysing the current market phase (Phase IV) and assessing how recent regulatory changes have affected the results observed in previous phases.

The paper is structured as follows. In Section 2, we describe the EU-ETS and analyse its recent history to contextualise our research. In Section 3, we review the literature and formulate the hypotheses. Section 4 describes the data set and methodology. In Section 5, we present the results. Finally, in Section 6, we outline the conclusions of the study.

2 | The European EU-ETS Emissions Market

The origin of emission rights markets dates back to the Kyoto Protocol, which was approved in 1997 and ratified in 2005. This protocol established binding emission reduction targets across different phases for 36 industrialised countries and the EU. The EU-ETS was adopted in the EU under Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 and its subsequent amendments. It applies to all EU member states, the European Free Trade Association countries (Iceland, Liechtenstein and Norway) and Northern Ireland for electricity generation (in accordance with the Northern Ireland Protocol).[1] Since its implementation in 2005, the EU-ETS has been mandatory for European companies that are required to participate on account of the GHG emissions resulting from their business activity. The scheme covers companies in the energy sector (electricity and heat generation), manufacturing industry (i.e., energy-intensive industrial sectors, including oil refineries, steelworks and the production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals), air operators and, from 2024, maritime transport.[2]

Under the European Climate Law, EU member states have committed to achieving climate neutrality by 2050. The European Commission's current plan targets a 55% emission reduction by 2030, relative to 1990 levels. In addition, the free allocation of emission allowances to companies has been reduced and will be progressively phased out from 2026. Furthermore, as part of the commitment, a new emissions trading system, ETS2, has been created to cover emissions from buildings, road transport and other sectors. It will come into operation in 2027. Climate neutrality or net zero emissions means that total GHG emissions must be equal to the amount removed from the atmosphere. The aim is to ensure that any unavoidable residual emissions are offset through actions that capture or absorb an equivalent amount of GHG, such as reforestation, soil restoration, carbon capture and storage and the acquisition of carbon emission allowances (European Commission 2024a).

The EU-ETS operates under a cap-and-trade model. Companies receive a maximum allocation of emission allowances. When they need to emit above this limit, they have two alternatives: acquire additional allowances in the market to avoid financial penalties or develop more sustainable production processes with lower environmental impact (i.e., environmental innovation). Each allowance (specifically, European Union Allowance or EUA) is equivalent to one tonne of carbon dioxide (CO_2) emitted. Since its launch in 2005, the EU-ETS has had four phases, during which adjustments have been introduced to improve its effectiveness and align it with the EU climate objectives: 2005 to 2007, 2008 to 2012, 2013 to 2020 and 2021 to 2030. Figure 1 shows the annual CO_2 and equivalent GHG emissions by the EU-27 countries (EU_27 emissions) over the period 2008–2023. Figure 1 also presents the free emission allowances (total allocation) and verified emissions from regulated facilities located in the EU-27 member states.

Although the EU-ETS was implemented in 2005, our study used data from 2008 onwards for several reasons. First, there was a lack of data during the early years. Second, CO_2 pricing was irrelevant and, in fact, reached zero in the early years, as demonstrated in Figure 2. Phase I (from 2005 to December 2007) was a period of adaptation and learning. During this phase, most allowances were allocated free of charge. Given the lack of verified emissions data, maximum emission limits were based on estimates, resulting in allowance oversupply and low prices.

Phase II ran from 2008 to December 2012. It coincided with the first commitment period of the Kyoto Protocol, during which countries set specific emission reduction targets. This phase saw the introduction of more stringent noncompliance penalties, the improvement of allowance allocation rules and a reduction in free allocation to approximately 90% of total allowances. Furthermore, the availability of verified annual emissions data enabled a 6.5% reduction in the maximum emission allowance cap. However, the 2008 economic crisis led to a greater-than-expected reduction in emissions, causing an allowance surplus and a collapse in prices (Gaztañaga et al. 2022).

Phase III ran from 2013 to 2020. It saw major changes, as well as the inclusion of the aviation sector the previous year as a regulated facility. The main modifications included the replacement of national emission caps with a single European-level cap, subject to an annual reduction of 1.74%. Furthermore, whereas emission allowances were freely allocated in the previous phases based on historical emission volumes, from 2013 onwards, allocation methodology began to consider facility efficiency criteria, with the most efficient facilities receiving higher allocations. In addition, free allocation became restricted to sectors at risk of carbon leakage spreading to the industry sector (i.e., if a sector could pass allowance costs to consumers, such as the energy sector, it no longer justified free allocation). Additionally, auctioning was introduced as the main allocation mechanism. Two further mechanisms were put in place to withdraw allowances (the back-loading system in 2014 and the Market Stability Reserve in 2019) in order to prevent sustained low pricing (Mañas-Álvarez et al. 2024).

The current phase is Phase IV (2021 to 2030). It has introduced developments in free allocation mechanisms. Although the allocation system remains similar to the one in Phase III, there is a mandate targeting a 30% reduction in free allocation (with respect to baseline entitlement) for all sectors not exposed to carbon leakage risk by 2026, with complete elimination by 2030. The annual emission cap reduction has been increased to 2.2%

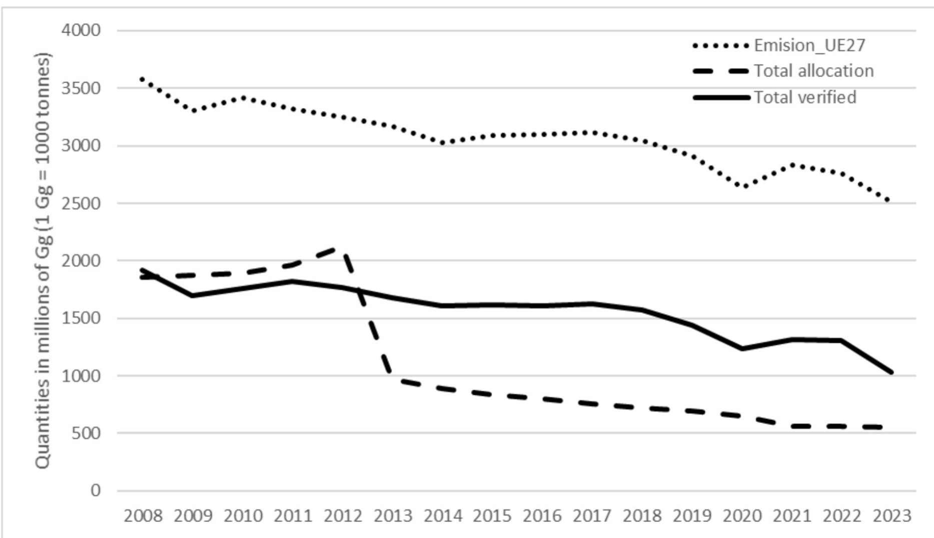

FIGURE 1 | **Evolution of** CO_2 **and equivalent emissions.** Authors based on data from the European Commission. Total CO_2 emissions data sourced from EDGAR emissions (European Commission 2024c). Remaining variables sourced from the Union Registry (European Commission 2024b).

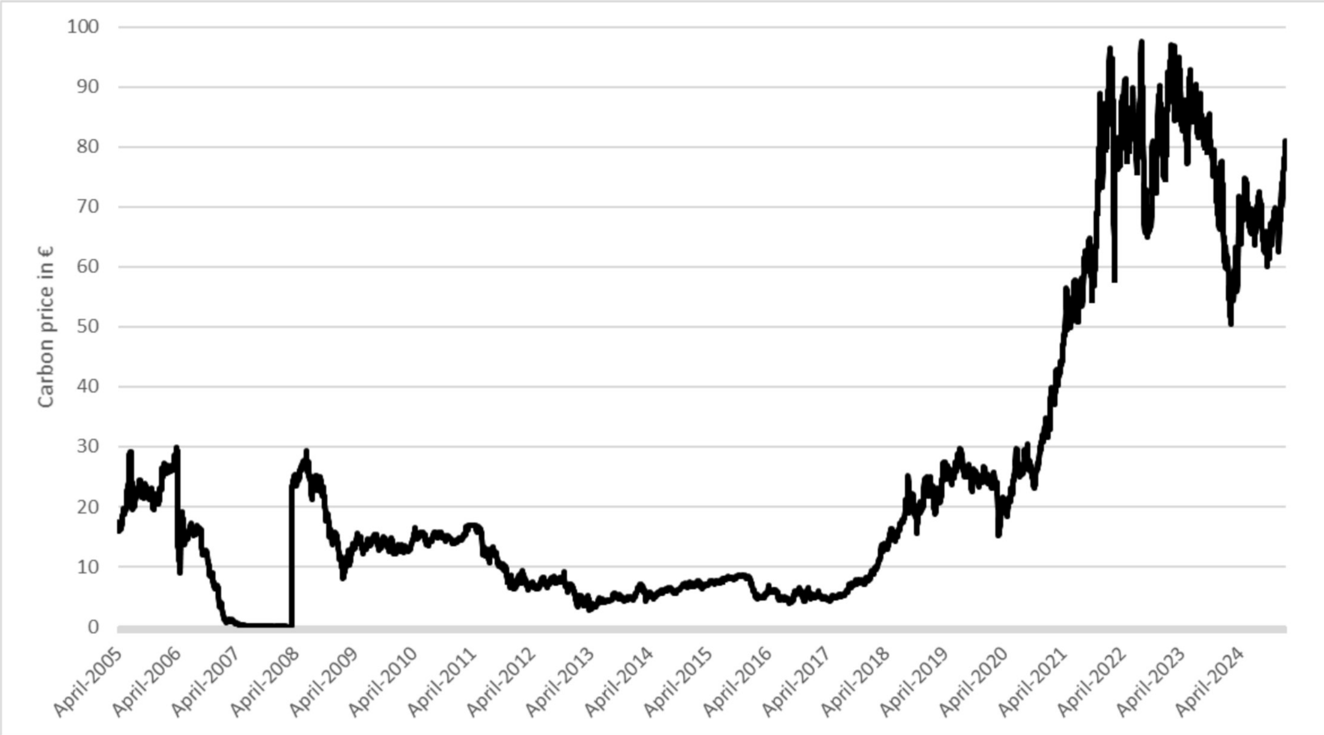

FIGURE 2 | **Evolution of carbon prices.** Authors based on data from Datastream (LEXCS01).

per year. It is complemented by additional measures within the climate package known as *Fit for 55*, which seeks to reduce net emissions by 55% by 2030 relative to 1990 levels.

In short, the changes introduced in each phase reflect the shift in EU-ETS towards a more stringent and effective system in the fight against climate change. The EU-ETS has established itself as the world's leading carbon market. It accounts for more than three quarters of global carbon trading and serves as a reference for analogous systems worldwide.

Table 1 illustrates the number of facilities, emissions, allocated allowances and verified emissions across Phases II, III and IV until 2023, both in aggregate annual terms and by sector. Based on EU registry data, there are three primary sectors: Sector 10, corresponding to aircraft operator activities; Sector 20, covering fuel combustion activities; and all remaining sectors grouped collectively. The data reveal that although the highest percentage of free allowances were allocated to fuel combustion facilities in Phase II, in Phase III onwards, there has been a substantial reduction in allocation to this sector, with other sectors proportionally receiving more free allocations.

Regarding verified emissions, Sector 20 (fuel combustion) accounts for the highest percentage of total emissions across all phases, declining from 63.42% in 2008 to 55.49% in 2023. In this sector, free allowance allocation fell from 56.73% in 2008 to 16.31% in 2023, while verified emissions decreased proportionally less. Consequently, these facilities have been forced to purchase emission allowances in the secondary market because emission reductions have not matched the pace of allowance allocation reductions. Conversely, in facilities in other sectors, the trend has been the opposite. They have received a higher percentage of allocations, while verified emissions declined from 36.58% in 2008 to approximately 33% during Phase III, rising to 39% in Phase IV. Sector 10 faced an initial allocation adjustment following its inclusion. Allowances decreased from 7.8% in 2012 to 3.06% in 2013. This adjustment appears attributable to calibration based on 2012 verified emissions (4.55%). Subsequently, allocation has stabilised at approximately 4%, slightly higher than verified emission levels. However, in 2020 and 2021, emissions fell due to the impact of the COVID-19 pandemic and the consequent reduction in activity.

3 | Literature Review and Hypotheses

3.1 | The Relationship Between Carbon Prices and CO_2 Emissions

The purpose of the EU-ETS is to incentivise emission reductions by encouraging companies to decrease their carbon intensity. They can do so by, for example, investing in renewable energies or energy efficiency technologies. Alternatively, they can internalise climate change costs by purchasing allowances to offset their emissions. Although policymakers prefer companies to reduce emissions while maintaining economic activity, firms interpret carbon allowance prices as market signals for optimal decision making. When carbon prices are low, companies tend to purchase emission allowances rather than make costly investments to reduce their emissions. Conversely, high carbon prices encourage firms to invest in emission reduction technologies rather than acquire emission allowances. As noted by Le and Azhgaliyeva (2023), companies invest in reducing emission

TABLE 1 | Evolution of EU-ETS facilities, emissions and allocation over time.

	Year	No. facilities	EU-27 emissions[a]	Total allocation[a]	Verified emissions[a]	Total allocation by sector S_10[b]	Total allocation by sector S_20[c]	Total allocation by sector Others	Verified emissions by sector S_10[b]	Verified emissions by sector S_20	Verified emissions by sector Others
Phase II	2008	10,303	3579798.47	1854209.05	1919624.76		56.73%	43.27%		63.42%	36.58%
	2009	10,375	3305536.81	1871448.86	1699679.96		56.64%	43.36%		66.18%	33.82%
	2010	10,351	3413786.63	1894832.06	1757665.46		57.15%	42.85%	0.03%	65.71%	34.26%
	2011	10,335	3317834.81	1959506.85	1824424.34		58.44%	41.56%	0.03%	67.12%	32.85%
	2012	11,094	3251387.67	2121181.77	1767735.26	7.80%	53.54%	38.66%	4.55%	64.01%	31.44%
Phase III	2013	10,747	3168344.67	968256.18	1676174.71	3.06%	36.27%	60.67%	2.96%	64.89%	32.15%
	2014	10,550	3025896.24	893272.71	1610831.20	3.30%	33.96%	62.74%	3.10%	63.58%	33.32%
	2015	10,308	3086214.92	838509.00	1618380.84	3.49%	31.29%	65.22%	3.21%	63.69%	33.10%
	2016	10,148	3094776.69	798631.46	1606650.92	3.64%	28.44%	67.92%	3.48%	63.02%	33.49%
	2017	10,042	3118707.52	755515.82	1622968.91	3.99%	25.88%	70.13%	3.54%	62.88%	33.58%
	2018	9,959	3049511.17	718454.34	1568623.63	4.18%	24.04%	71.77%	4.02%	61.45%	34.53%
	2019	9,851	2908156.85	695612.12	1435289.36	4.71%	21.96%	73.33%	4.67%	58.24%	37.09%
	2020	9,536	2641187.92	651247.41	1237223.57	5.12%	18.28%	76.60%	2.11%	58.17%	39.72%
Phase IV	2021	8,711	2833755.06	564394.21	1319326.24	4.56%	16.64%	78.80%	2.21%	58.88%	38.91%
	2022	8,614	2756906.30	561775.42	1308851.99	4.41%	16.66%	78.93%	3.82%	59.31%	36.87%
	2023	8,527	2512067.78	556187.30	1030452.37	4.38%	16.31%	79.31%	4.66%	55.49%	39.85%

Source: Authors based on data from the European Commission. Total CO_2 emissions data sourced from the EDGAR emissions database (European Commission 2024c). Remaining variables were sourced from the Union Registry (European Commission 2024b).

[a]Quantities in Gg (1 Gg = 1000 t).

[b]Sector: Aircraft operator activity.

[c]Sector: Fuel oil combustion activities.

intensity when the marginal cost of such investment per carbon unit falls below the carbon price, continuing until cost equalisation occurs and the policy is effective. When the marginal cost of this investment exceeds carbon prices, companies choose to purchase carbon emission allowances. Therefore, carbon pricing can have different impacts on different companies and does not always result in emission reductions. Indeed, emission allowance systems can produce unintended consequences for regulated firms. Such consequences include a reduction in production or so-called carbon leakage, where firms relocate their business to another country with less stringent or no environmental regulations.

The literature explores the impact of carbon prices on emission levels, mainly at the aggregate country or regional levels (Green 2021; Rafaty et al. 2025). Most studies have confirmed the effectiveness of carbon pricing in reducing emissions. However, the impact remains modest, with estimated annual emission reductions ranging from 0% to 2% at the aggregate level. Despite these findings, there is little evidence at the firm level. Although most studies have shown positive relationships between carbon pricing and emission reductions, the results vary.

Several studies have documented a positive relationship between carbon pricing and emission reductions (or negative with GHG emissions). For instance, Adamolekun (2024) examined the impact of carbon pricing on GHG emissions by European companies, confirming the effectiveness of carbon policies after observing a negative relationship between carbon prices and corporate GHG emissions. Colmer et al. (2023) found that emissions trading markets achieved 14%–16% CO_2 emission reductions among French manufacturing companies. They also found no evidence of carbon leakage, meaning that regulated firms did not relocate to unregulated jurisdictions or sectors. Similarly, Dechezleprêtre et al. (2023) showed that the implementation of the EU-ETS reduced carbon emissions by regulated companies, particularly during Phase II from 2008 to 2012. Focusing on other emissions trading markets, Le and Azhgaliyeva (2023) analysed the effect of carbon pricing policies in Japan, Korea and China on GHG emissions by manufacturing companies. They found direct relationships between carbon prices and GHG emission reductions in Japan and Korea, both in absolute terms and relative to company revenues. Meanwhile, Martinsson et al. (2024) focused on another carbon policy. Instead of analysing emissions markets, they studied carbon taxation, finding a negative relationship between CO_2 emissions and the marginal cost of emitting CO_2 for Swedish manufacturing companies.

Conversely, other studies in European contexts have found that the implementation of the EU-ETS has not reduced emissions or their intensity. At the firm level, Calel (2020) examined regulated companies in the United Kingdom and found no evidence of an improvement in emission intensity following the launch of the EU-ETS. Similarly, Jaraité and Di Maria (2016) conducted a plant-level study for Lithuania, observing that emission levels did not fall and that there was only a slight improvement in emission intensity during the first year of the EU-ETS. At the facility level, Klemetsen et al. (2020) analysed Norwegian regulated plants, finding weak evidence of emission reductions in Phase II, with no corresponding emission intensity improvements across any phase.

In view of these findings and the fact that our study is based on firm-level analysis of the period from Phase II inception to 2023 (encompassing market changes such as free allowance reductions and carbon price increases), we expect to observe an inverse relationship between the price of emission allowances and corporate GHG emissions. Specifically, increases in carbon prices should lead to lower emissions, whereas carbon price decreases should result in greater emissions.

H1. *The price of emission allowances is inversely related to corporate GHG emissions (*i.e.*, positively related to a reduction in GHG emissions).*

3.2 | The Relationship Between Carbon Prices and Green R&D

As previously noted, one of the aims of the EU-ETS is to encourage investment in low-carbon technologies to reduce CO_2 emissions and thus avoid high production costs. According to the hypothesis of induced innovation formulated by Hicks (1932), an increase in the price of a production factor stimulates innovation to reduce the use of that factor. Applying this hypothesis to the context of emissions trading markets, carbon price increases would encourage regulated companies to invest in cleaner and more efficient technologies to reduce their emissions and associated costs. Similarly, Porter (1991) argued that environmental regulations can stimulate innovation and improve production efficiency, suggesting that climate policies would not compromise the competitive advantage of companies and could even strengthen it. One of the key ideas identified by Porter and Linde (1995) is that such regulation should be flexible and allow companies to adapt optimally either through output-focused improvements in production processes or waste management or through input-focused modifications such as alternative raw material use.

At the empirical level, various studies have explored the effect of the EU-ETS on innovation. Some have been conducted at the regional or national level. For instance, Lim and Prakash (2023) analysed 38 OECD countries, finding that the adoption of decarbonisation and CO_2 pricing policies was associated with an increase in patents for climate change mitigation technologies. At the firm level, most research has examined how the implementation of emissions trading markets stimulates technological innovation for climate change mitigation rather than analysing the impact of carbon prices. Calel and Dechezleprêtre (2016) observed that the EU-ETS has increased low-carbon innovation among regulated European companies, whether measured through R&D expenditure or low-carbon patent activity.

Calel (2020) noted that business investment can materialise through the adoption of existing technologies within production processes or through innovation in new technologies based on renewable energy, recycling and efficient waste management. In a study of the British market, Calel (2020) found that regulated companies have increased low-carbon patents and R&D expenditure since EU-ETS participation but have not adopted technologies that reduce CO_2 intensity. Despite these findings, Calel (2020) predicted that investment in technology will yield greater emission reductions, mitigating the effects of climate change in the long term. Goerger (2021) similarly observed an increase in technologies aimed at mitigating climate change, which has also grown across the EU-ETS phases. Similar results have emerged from studies of carbon markets beyond Europe. For example, Lin and Wesseh (2020) studied the impact of carbon prices on companies' R&D expenditure within the CN-ETS, observing positive effects of CO_2 prices on R&D expenditure. Additional CN-ETS-oriented studies by Shao et al. (2023), Yang et al. (2023) and Zhu et al. (2019) have demonstrated that emissions trading markets stimulate technology development for climate change mitigation.

However, findings regarding emissions trading markets and innovation investment lack consensus. For example, scholars observed no impact of the EU-ETS on green innovation in the cases of Sweden (Löfgren et al. 2014) and Norway (Lunde 2022). Others, including Chen et al. (2021) and Zhang et al. (2022) for the Chinese market, have identified a negative effect of the CN-ETS on low-carbon technology patents.

In view of these findings and the fact that it has been some time since the implementation of the EU-ETS and the corresponding phase-by-phase adjustments, we expect to observe a positive relationship between emission allowance prices and green R&D. Higher allowance costs should encourage corporate innovation investment to reduce emissions without compromising production capacity. Specifically, carbon price increases should lead to an increase in green R&D investment, whereas decreases should reduce corporate investment in sustainability. Accordingly, we formulate the following hypothesis:

H2. *The price of emission allowances is inversely related to green R&D.*

3.3 | The Relationship Between CO_2 Emissions and Green R&D

Technological change is necessary to address climate change without compromising economic growth. The fossil fuel-based economic model developed over the past two centuries has caused environmental degradation that must be reversed. The transition from fossil fuels (oil, coal and natural gas) to renewable energy sources (e.g., solar, wind and hydroelectric) requires technological innovation to ensure the sustainable management of energy resources without diminishing production capacity (for a systematic literature review, see Chen et al. 2024; Teixidó et al. 2019). Measures that can mitigate the impact of business production on the environment include the implementation of environmental management systems, pollution prevention, energy efficiency, carbon management and reuse and recycling (Albitar et al. 2023; Calel 2020). Environmental innovation or eco-innovation is a strategy that simultaneously improves corporate environmental performance and economic performance (Lee and Min 2015). However, the absence of a mechanism that places a price on GHG emissions or the absence of a market price (Phase I) has not encouraged companies to invest in green R&D because there has been no incentive to reduce such emissions. We argue that pollution pricing, as discussed previously, can stimulate environmental innovation and consequently reduce GHG emissions. For example, studies have demonstrated that investment in innovation helps reduce CO_2 emissions, as discussed later.

Some authors have analysed the impact of R&D on emissions without explicitly considering emission rights markets. For instance, Albitar et al. (2023) found that environmental innovation reduced CO_2 emissions among London Stock Exchange-listed companies, noting that effective corporate governance enhanced these reductions. Apergis et al. (2013) performed a country-level study for Germany, France and the United Kingdom, observing a positive relationship between R&D expenditure and CO_2 emission reductions. Similarly, Gonenc and Poleska (2023) analysed the role of R&D expenditure in reducing corporate GHG emissions across an international sample, confirming that higher R&D expenditure leads to emission reductions, which are greater among multinationals than domestic companies. Furthermore, they identified indirect carbon leakage to developing countries with presumably less stringent environmental regulations. For the Japanese market, Lee and Min (2015) confirmed that greater investment in green R&D by manufacturing companies (eco-innovation in products, processes and operations) reduced GHG emissions. Similar country-level research has been performed by Fernández et al. (2018). They explored whether environmental and total innovation efforts have a positive impact on CO_2 emission reductions across the EU, United States and Japan, confirming a positive impact for the EU and United States. Likewise, Puertas and Marti (2021) analysed the determinants of GHG emissions in OECD countries and confirmed that eco-innovation enables a reduction in GHG emissions.

Studies that consider the existence of the EU-ETS include that of Colmer et al. (2023), who presented evidence that the implementation of the EU-ETS reduced emissions without restricting economic activity because companies invested in energy-efficient technologies. Khurshid et al. (2023) conducted a regional study for Central and Eastern Europe, finding that innovation and environmental policies encouraged emission reductions.

Therefore, we expect that greater investment in green R&D, environmental innovation or eco-innovation reduces GHG emissions. We thus formulate the following hypothesis:

H3. *There is an inverse relationship between green R&D and GHG emissions.*

Finally, if these hypotheses are confirmed, it may imply that environmental innovation mediates the effect of carbon prices on GHG emissions. Specifically, if (i) carbon prices significantly affect GHG emissions in the absence of the mediating variable (H1), (ii) carbon prices significantly affect environmental innovation (H2) and (iii) environmental innovation (without considering carbon prices) significantly affects GHG emissions (H3), then we can say that environmental innovation is a mediator if the effect of carbon prices on GHG emissions diminishes when environmental innovation is included as an explanatory variable.

However, existing evidence presents conflicting findings regarding this mediating effect. The expected relationship between environmental innovation and GHG emissions may prove non-significant when carbon prices and environmental innovation are analysed together. For example, Rogge (2016) acknowledged that the EU-ETS is important for decarbonisation but found it to have a limited impact on innovation. Specifically, the market has mainly influenced organisational innovations, with minimal effects on emission reduction strategies. Similarly, from their literature review, Teixidó et al. (2019) concluded that the EU-ETS has been more effective at stimulating low-carbon technological innovation than promoting the adoption of such technology. After reviewing numerous studies, Chen et al. (2024) reached similar conclusions, stating that emissions trading markets provide moderate incentives for technological innovation.

In relation to technological innovation, Dill (2024) analysed whether green bond emissions (i.e., raising funds for environmentally sustainable projects) and CO_2 pricing are related to GHG emissions. The results revealed that carbon prices and green bond issuance were individually associated with emission reductions. However, the interaction was not found to be statistically significant.

Therefore, in view of the available evidence, we treat the mediating effect as an open empirical question. The following hypotheses are thus proposed:

H4a. *Green R&D mediates the relationship between carbon prices and GHG emissions.*

H4b. *Green R&D does not mediate the relationship between carbon prices and GHG emissions.*

Figure 3 graphically represents the proposed hypotheses.

4 | Data and Methodology

4.1 | Data

Based on European Commission data on climate action (European Commission 2024b), we gathered data on verified emissions and allowances for facilities under the EU-ETS from 2008 to 2023 (inclusive). From the same source, we obtained the list of EU-ETS operators (i.e., the list of facilities linked to the account holder, which, in each case, is usually the company that owns the facility). We thus found 10,582 account holders operating across 189,969 European facilities regulated by the EU-ETS during the study period.

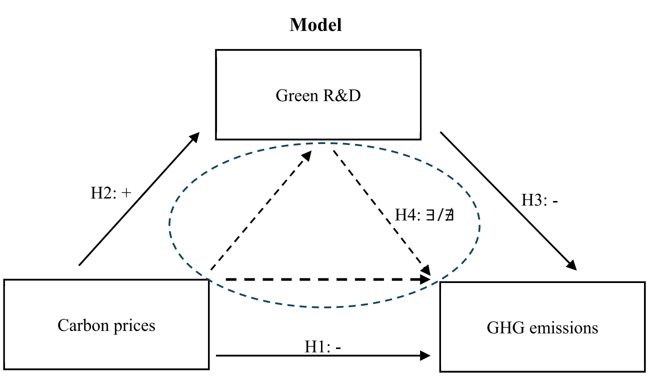

FIGURE 3 | **Model.** Authors.

In parallel, we selected 6258 companies from Thomson Reuters Eikon Refinitiv based in one of the EU-27 countries and identified those owning EU-ETS-regulated facilities. This process required matching the name of the account holder with their corresponding entries in Thomson Reuters Eikon Refinitiv. Because of naming variations and data limitations, we successfully matched 8068 of the 10,582 account holders. For these matched companies, we identified their immediate and ultimate parent companies, given that many account holders were subsidiaries of listed companies. Through this matching process, we deduced which of the 6258 companies operated EU-ETS facilities. Our final sample consisted of companies for which Thomson Reuters Eikon provided complete data on our variables of interest for the period 2008 to 2023: GHG emissions, proxied by CO_2 emissions; corporate environmental R&D measures; and sales volume, used as a control variable for firm size or production volume. These data requirements reduced our sample to 1948 companies, yielding 17,038 company-year observations. Table 2 shows the distribution of the companies in the sample by country and sector.

Regarding environmental innovation measurement, we initially considered the *Environmental R&D Expenditures* field in Thomson Reuters Eikon Refinitiv. This field captures total R&D costs for environmentally focused products and services aimed at reducing environmental impact. However, this variable was discarded due to a lack of data on companies. To overcome this drawback, we proxied companies' green R&D using the environmental innovation score variable. This variable captures a

TABLE 2 | Variable name, source and definition.

Variable	Source	Definition
Firms GHG emissions (E_CO_2)	Thomson Reuters Eikon	Annual GHG emissions of the company, proxied by its annual CO_2 emissions
Environmental innovation score (R&D_green)	Thomson Reuters Eikon	This variable captures a company's ability to reduce environmental costs and burdens for customers and therefore create new market opportunities through new environmental technologies and processes or eco-designed products
Carbon price (P_CO_2)	Datastream	This variable shows the average daily price of carbon for each year in the sample
Sales	Thomson Reuters Eikon	Annual sales volume of the company
Annual CO_2 emission by country ($E_CO_2$country)	European Commission's EDGAR	Annual CO_2 emission volumes by country

Source: Authors.

TABLE 3 | Sample by sector and country.

NAICS sector[a] and country	11	21	22	23	31	42	44	48	51	52	53	54	55	56	61	62	71	72	81	Total
Austria	0	0	2	3	26	1	0	3	2	6	2	1	0	0	0	0	0	1	0	47
Belgium	1	1	1	3	33	2	1	3	6	5	10	5	0	0	0	1	0	0	1	73
Bulgaria	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	3
Croatia	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Cyprus	2	1	0	1	3	1	1	1	1	1	0	0	0	0	0	0	0	0	0	12
Czech	0	0	1	0	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	4
Denmark	0	0	2	4	37	3	1	6	4	7	2	11	0	1	0	0	0	0	0	78
Estonia	0	0	1	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	4
Finland	0	1	1	7	51	1	5	2	14	4	2	9	0	1	0	2	0	0	0	100
France	2	6	11	6	135	7	10	4	28	16	13	46	1	4	1	4	4	3	1	302
Germany	1	0	9	9	186	9	10	6	48	27	11	35	0	3	0	6	2	1	0	363
Greece	2	1	5	3	18	2	2	4	3	5	2	8	0	0	0	0	1	0	0	56
Hungary	0	0	0	2	3	1	0	0	1	2	0	0	0	0	0	0	0	0	0	9
Ireland	1	2	0	2	28	4	1	1	6	5	2	5	0	2	0	0	0	1	1	61
Italy	0	0	14	4	76	4	3	4	16	23	1	10	0	2	0	1	1	0	0	159
Latvia	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	3
Lithuania	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
Luxembourg	1	1	1	0	10	1	3	2	5	2	5	6	0	2	0	0	0	0	0	39
Malta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Netherlands	0	3	0	5	28	1	4	3	11	10	5	8	0	3	0	0	1	2	0	84
Poland	0	3	5	4	26	3	4	1	12	10	1	7	0	1	0	0	0	0	0	77
Portugal	0	1	2	1	4	0	2	1	2	2	0	1	0	0	0	0	0	0	0	16
Romania	0	0	1	1	11	1	0	2	1	4	0	1	0	0	0	0	0	1	0	23
Slovak	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
Slovenia	0	0	0	0	2	0	0	0	1	1	0	0	0	0	0	0	0	1	0	5
Spain	0	1	7	12	31	1	3	3	4	10	3	12	0	4	0	1	0	2	0	94
Sweden	1	3	3	9	150	10	11	0	35	24	22	45	0	6	0	5	2	2	1	329
Total	11	25	66	76	867	52	61	47	201	167	82	211	1	29	1	21	12	14	4	1948

Source: Authors.

[a]11 agriculture, forestry, fishing, and hunting; 21 mining, quarrying, and oil and gas extraction; 22 utilities; 23 construction; 31 manufacturing; 42 wholesale trade; 44 retail trade; 48 transportation and warehousing; 51 information; 52 finance and insurance; 53 real estate and rental and leasing; 54 professional, scientific, and technical services; 55 management of companies and enterprises; 56 administrative and support and waste management and remediation services; 61 educational services; 62 health care and social assistance; 71 arts, entertainment, and recreation; 72 accommodation and food services; 81 other services (except public administration).

company's ability to reduce environmental costs and burdens for customers and therefore create new market opportunities through new environmental technologies and processes or eco-designed products.

Additional variables included carbon price, gathered from Datastream and annual CO_2 emission volumes for each EU-27 member state, sourced from the European Commission's EDGAR emissions database (European Commission 2024c). This variable proxied the level of industrialisation and development of the country. These variables are summarised in Table 3.

Table 4 presents the correlation matrix and descriptive statistics for the variables used in this study. The correlation coefficients indicated no multicollinearity concerns because all

TABLE 4 | Descriptive statistics and correlation matrix.

	(1)	(2)	(3)	(4)	(5)
(1) Ln (E_CO_2)	1				
(2) R&D_green	0.353	1			
(3) P_CO_2	−0.287	−0.042	1		
(4) Ln (Sales)	0.764	0.405	−0.202	1	
(5) Ln ($E_CO_2$country)	0.159	0.093	−0.1	0.188	1
Observations	9,149	10,208	17,038	17,028	17,038
Mean	11.331	40.435	29.596	20.08	18.862
SD	2.965	33.202	28.163	2.803	1.216
Minimum	−1.897	0.000	4.476	5.336	14.381
Maximum	19.223	99.902	83.626	26.499	20.537

Source: Authors.

values remained within acceptable thresholds. Data availability differed across variables. However, restricting the study to company-year observations with complete data for all variables would have substantially reduced the sample size, potentially limiting the generalisability of our findings.

4.2 | Methodology

Given the structure of our data, we performed our estimates using panel data analysis. The estimators in panel data analysis are more accurate than those in other techniques such as generalised least squares (GLS). For example, the panel data technique captured unobservable heterogeneity both between individuals in the sample and over time (Arellano 1992).

In the first step, to test Hypotheses 1 and 2, Equation 1 shows the static analysis formula used to estimate a model where the dependent variable was either GHG emissions or R&D expenditure, with emphasis on environmental R&D by EU–27 companies. These variables were explained by carbon prices and relevant control variables. All estimates were conducted in Stata.

$$
\begin{aligned}
DV_{it} = {} & C + \beta_1 P\_CO_{2_t} + \beta_2 P\_CO_{2_{t-1}} \\
& + \beta_3 Inst_{it} + \beta_4 \left(P\_CO_{2_t} \times Inst_{it}\right) + \beta_5 \left(P\_CO_{2_{t-1}} \times Inst_{it}\right) \\
& + \beta_6 Phase\_III + \beta_7 Phase\_IV + \beta_8 \ln\left(Sales_{it}\right) \\
& + \beta_9 \ln\left(E\_CO_2country_t\right) + \varepsilon_{it}
\end{aligned} \tag{1}
$$

Where:

- DV_{it} is the dependent variable—CO_2 emissions in logarithmic terms (*ln[E_CO$_2$]*) or environmental innovation score (R&D_green)—of company i in year t.
- The explanatory variables are:
  - Average daily carbon price (*P_CO_2*) in year t and in the previous year ($t - 1$).
  - A dummy variable (*Inst*) equal to 1 if company i operated EU-ETS facilities at time t and zero otherwise.
  - Two dummy variables (*Phase_III* and *Phase_IV*) equal to 1 during Phase III and Phase IV of the EU-ETS, respectively, and zero otherwise.
  - A variable (Sales) reflecting the size or production volume of company *i* in year *t*.
  - Finally, a variable capturing the CO_2 emission volume in year t of the country where the company was headquartered (*$E\_CO_2country$*).
  - Two interaction terms were created to accompany β4 and β5 to capture the varying effect of carbon prices on the dependent variable for companies operating EU-ETS facilities.

We subsequently contrasted the results for the static models with the results using the dynamic specification shown in Equation 2. This specification included the lagged dependent variable as a regressor. This dynamic specification was estimated using the generalised method of moments (GMMs) put forward by Arellano and Bond (1991).

$$
\begin{aligned}
DV_{it} = {} & C + \beta_0 DV_{it-1} + \beta_1 P\_CO_{2_t} + \beta_2 P\_CO_{2_{t-1}} + \beta_3 Inst_{it} \\
& + \beta_4 \left(P\_CO_{2_t} \times Inst_{it}\right) + \beta_5 \left(P\_CO_{2_{t-1}} \times Inst_{it}\right) + \beta_6 Phase\_III \\
& + \beta_7 Phase\_IV + \beta_8 \ln\left(Sales_{it}\right) + \beta_9 \ln\left(E\_CO_2country_t\right) + \varepsilon_{it}
\end{aligned} \tag{2}
$$

To test Hypotheses 3 and 4, we estimated the models presented in Equations 3 and 4, respectively. In estimating these models, we employed a dynamic panel estimated using GMM.

$$
\begin{aligned}
\ln\left(E\_CO_{2_{it}}\right) = {} & C + \beta_0 \ln\left(E\_CO_{2_{it-1}}\right) + \beta_1 Inst_{it} + \beta_2 \left(R\&D\_green_{it}\right) \\
& + \beta_3 Phase\_III + \beta_4 Phase\_IV + \beta_5 \ln\left(Sales_{it}\right) \\
& + \beta_6 \ln\left(E\_CO_2country_t\right) + \varepsilon_{it}
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
\ln\left(E\_CO_{2it}\right) = {} & C + \beta_0 \ln\left(E\_CO_{2it-1}\right) + \beta_1 P\_CO_{2_t} + \beta_2 P\_CO_{2_{t-1}} \\
& + \beta_3 Inst_{it} + \beta_4 \left(P\_CO_{2_t} \times Inst_{it}\right) + \beta_5 \left(P\_CO_{2_{t-1}} \times Inst_{it}\right) \\
& + \beta_6 \left(R\&D\_green_{it}\right) + \beta_7 Phase\_III + \beta_8 Phase\_IV \\
& + \beta_9 \ln\left(Sales_{it}\right) + \beta_{10} \ln\left(E\_CO_2country_t\right) + \varepsilon_{it}
\end{aligned} \tag{4}
$$

The consistency of the GMM estimator requires certain assumptions to be met. Namely, it requires the use of valid instruments and the absence of second-order autocorrelation (AR2) in residuals. We employed Hansen's overidentification test to verify the validity of the instruments and to examine autocorrelation patterns. We expected first-order but no higher-order autocorrelation in the error terms.

Additionally, to test for the mediation effect, we applied the Stata command "*sgmediation2*" (Mize 2022). This command performs the Sobel–Goodman test and provides evidence of the aforementioned requirements to accept the existence of such an effect. In addition, as suggested by Mize (2022), given that the Sobel–Goodman test has low statistical power, we used bootstrapping to calculate the statistical significance of the parameters.

5 | Results

Before commenting on the results for Hypotheses 1 and 2 (presented in Table 5) for GHG emissions and the proxy used to measure corporate green R&D, we addressed potential model specification issues. The Hausman test was applied to each model to analyse whether the individual effects followed random effects (REs) or fixed effects (FEs) behaviour. The test indicated that estimation with FEs was more suitable than estimation with REs because there was a correlation between the individual effects and the explanatory variables. In GMM methodology, estimation consistency depends on the validity of the instruments and the absence of second-order autocorrelation. The Hansen test confirmed instrument validity, and the autocorrelation tests led to the rejection of the hypothesis of the absence of first-order autocorrelation and acceptance of second-order autocorrelation (Table 5).

Focusing on companies' GHG emissions, we observed a significant negative relationship with carbon price in year t. Specifically, as purchasing emission allowances became more expensive, companies reduced their emissions, regardless of EU-ETS participation. In addition, past changes in carbon prices significantly affected CO_2 emissions only for companies operating EU-ETS facilities. Therefore, these findings confirm Hypothesis 1 and are consistent with those of Adamolekun (2024), who observed a negative relationship between carbon prices and GHG emissions. They are also consistent with the findings of Dechezleprêtre et al. (2023) and Colmer et al. (2023), who observed that the EU-ETS has successfully reduced GHG emissions.

Regarding control variables, the results were consistent across estimation methods. However, we chose to interpret the results from the GMM analysis because it offered more efficient and less biased results. There was no difference in behaviour depending on whether the company had facilities affected by the EU-ETS. In addition, as expected, sales volume (used to indicate larger companies or those with higher production volumes) had a significant positive relationship with GHG emissions. Similarly, being headquartered in countries with high CO_2 emissions, a variable that potentially reflects national development or industrialisation levels, had a significant positive relationship with GHG emissions. Finally, the Phase_III variable had a significant negative value, indicating significant emission reductions attributable to factors including reduced emission allowances, the change in free allowance allocation mechanisms and, among others, the effects on business activity due to COVID-19.

With regard to the influence of carbon prices on environmental innovation, it was impossible to find a variable that reflected companies' efforts in this area. Therefore, we proxied this variable using the environmental innovation score, which captured a company's ability to reduce environmental costs and burdens for customers and therefore create new market opportunities through new environmental technologies and processes or eco-designed products. As expected (Table 5), there was a direct relationship between carbon price in year t and the amount allocated to corporate green R&D. Furthermore, the GMM results showed that, for companies operating EU-ETS facilities, there was a significant positive differential relationship between environmental innovation and carbon price in year t. These findings support Hypothesis 2 and are in line with research by Calel (2020), Calel and Dechezleprêtre (2016), Goerger (2021) and Rogge (2016). These studies document the positive impact of the EU-ETS on business innovation, although certain studies have indicated limited effects (Rogge 2016).

As for the analysis of GHG emissions, we did not observe any differentiating behaviour depending on whether the company had facilities in the EU-ETS. This result is consistent with the conclusions of Miller (2015), who reported an induced innovation effect in unregulated companies. However, this result contrasts with the findings of Calel and Dechezleprêtre (2016), who observed small and statistically nonsignificant spillover effects.

Regarding the control variables, firm size had a positive influence on companies' environmental innovation. Conversely, the environmental innovation score had a significant negative relationship with the Phase IV variable. This result may reflect increased regulatory pressure in recent years, with sustainability requirements affecting operations. It may reflect the association of environmental innovation with higher costs, a lack of short-term results and a surge in climate change denial movements linked to misinformation, economic interests and political polarisation.

Focusing on the relationship between environmental innovation and CO_2 emissions (Column 2 of Table 6), we observed a significant negative relationship between these variables, confirming Hypothesis 3. This result is in line with previous research (Albitar et al. 2023; Gonenc and Poleska 2023; Lee and Min 2015) that establishes a relationship between environmental innovation and CO_2 emission reductions.

However, when carbon price was introduced as an independent variable (Columns 3 and 4 of Table 6), the effect of green R&D on GHG emissions became nonsignificant (i.e., the effect was absorbed by carbon price). This finding implies the absence of a mediating effect. The Sobel–Goodman test (Table 7) confirmed this absence of mediation by rejecting the mediation hypothesis. These results validate Hypothesis 4b and corroborate the findings of previous studies (Chen et al. 2024; Rogge 2016; Teixidó et al. 2019), which document the limited effects of corporate environmental innovation on GHG emissions.

TABLE 5 | Relationship of carbon prices with GHG emissions and green R&D.

	Dependent variable: Ln (E_CO_2)			Dependent variable: R&D_green		
	Pooled model	Fixed effects model	Dynamic model: GMM	Pooled model	Fixed effects model	Dynamic model: GMM
Dependent variable$_{t\text{-}1}$			0.731*** (0.051)			0.772*** (0.030)
P_CO_{2t}	−0.01*** (0.003)	−0.002* (0.001)	−0.002* (0.001)	−0.075 (0.049)	0.137*** (0.039)	0.039* (0.022)
$P\_CO_{2t\text{-}1}$	0.001 (0.002)	0.001 (0.001)	0.001 (0.001)	0.089** (0.028)	−0.014 (0.026)	−0.016 (0.017)
$Inst_t$	1.555*** (0.151)	0.014 (0.067)	0.257 (0.241)	2.407 (2.764)	−3.209 (2.908)	−0.482 (3.85)
$P\_CO_{2t} \times Inst_t$	0.012*** (0.003)	0.001 (0.001)	0.001 (0.001)	0.096* (0.058)	−0.006 (0.044)	0.064* (0.034)
$P\_CO_{2t\text{-}1} \times Inst_t$	−0.008*** (0.002)	−0.003** (0.001)	−0.002** (0.001)	−0.095* (0.050)	−0.026 (0.040)	−0.048 (0.037)
Phase_III	−0.284*** (0.053)	−0.108** (0.04)	−0.039* (0.022)	2.051* (1.074)	5.032*** (1.115)	−0.417 (0.438)
Phase_IV	−0.303*** (0.086)	−0.157** (0.052)	−0.003 (0.041)	3.762** (1.667)	2.814** (1.434)	−2.685** (0.948)
Ln ($Sales_t$)	0.978*** (0.037)	0.526*** (0.079)	0.293*** (0.064)	6.707*** (0.437)	0.684 (1.022)	1.817** (0.657)
Ln ($E\_CO_2country_t$)	−0.001 (0.041)	0.661*** (0.186)	0.467*** (0.115)	1.009 (0.699)	−8.92* (5.105)	−0.553 (2.032)
Intercept	−8.061*** (1.197)	−12.3*** (3.648)	−6.083 (4.989)	−110.522*** (19.017)	187.695* (98.594)	−59.154 (78.420)
Control industry	Yes	Yes	Yes	Yes	Yes	Yes
Cluster (firm)	Yes	Yes	Yes	Yes	Yes	Yes
Observations	8,158	8,158	7,778	9,115	9,115	8,759
R^2	0.729			0.276		
R-within		0.096			0.069	
R-between		0.360			0.023	
R-overall		0.335			0.012	
Hausman test		0.000			0.000	
Instruments (number)			229			246
Groups (number)		1,186	1,172		1,283	1,274
AR(1)			0.000			0.000
AR(2)			0.113			0.409
Hansen test			0.121			0.130

Source: Authors.
*indicate significant results at the 90 levels.
**indicate significant results at the 95% level.
***indicate significant results at the 99% level.

TABLE 6 | Relationship of green R&D with GHG emissions.

	Dependent variable: Ln (E_CO_2)		
	Dynamic model: GMM		
Dependent variable$_{t-1}$	0.604*** (0.064)	0.668*** (0.054)	0.673*** (0.062)
P_CO_{2t}		−0.002** (0.001)	−0.002** (0.001)
P_CO_{2t-1}		0.0001 (0.001)	0.0002 (0.001)
$Inst_t$.	0.406** (0.208)	0.042 (0.048)	−0.039 (0.227)
$P\_CO_{2t} \times Inst_t$			0.0002 (0.001)
$P\_CO_{2t-1} \times Inst_t$			−0.002** (0.001)
$R\&D\_green_t$	−0.005* (0.003)	−0.001 (0.001)	−0.001 (0.001)
Phase_III	0.016 (0.025)	−0.022 (0.02)	−0.03 (0.022)
Phase_IV	−0.016 (0.037)	0.037 (0.043)	0.037 (0.039)
Ln ($Sales_t$)	0.339*** (0.065)	0.344*** (0.069)	0.365*** (0.073)
Ln ($E\_CO_2country_t$)	0.558*** (0.116)	0.468*** (0.125)	0.405** (0.138)
Intercept	−3.077 (8.879)	−8.235 (7.791)	−4.753 (13.592)
Control industry	Yes	Yes	Yes
Cluster (firm)	Yes	Yes	Yes
Observations	7777	7777	7777
Instruments (number)	188	272	272
Groups (number)	1172	1172	1172
AR(1)	0.000	0.000	0.000
AR(2)	0.148	0.112	0.117
Hansen test	0.198	0.142	0.117

Source: Authors.
*indicate significant results at the 90 levels.
**indicate significant results at the 95% level.
***indicate significant results at the 99% level.

6 | Conclusions

The EU has led the fight against climate change in recent decades. It has done so through both its commitments and the scope of its policies. Since its creation in 2005, the EU Emissions Trading System (EU-ETS) has been the cornerstone of European climate policy and decarbonisation strategy, with the primary objective of reducing GHG emissions.

By focusing on carbon prices, this study examined whether the EU-ETS has effectively incentivised the corporate transition towards sustainable production processes by encouraging GHG emission reductions and fostering innovation in clean and efficient technologies. Our findings demonstrate that the EU-ETS is fulfilling its objective. Specifically, the findings imply that carbon price has a negative relationship with corporate CO_2 emissions and a positive relationship with innovation in low-carbon technologies. These relationships hold across both regulated and unregulated sectors, although they are particularly pronounced among companies operating facilities included in the EU-ETS.

Our results show that carbon pricing is an effective instrument for enhancing corporate environmental performance and strengthening sustainability commitments. However, despite the direct relationship between carbon prices and green innovation, the analysis of the relationship between green innovation and CO_2 emissions suggests that innovation efforts focus primarily on technology rather than practical applications. Consequently, our results confirm that green innovation exerts a limited impact on GHG emissions, with carbon pricing acting as the main driver of corporate GHG emission reductions.

6.1 | Implications

The results are of interest to different stakeholders. For companies, they provide insight into key aspects of operations such as the environmental impact of their business activity, the internalisation of environmental costs and the development of innovation in clean technologies. For policymakers and regulators, the evidence verifies the effectiveness of existing mechanisms and suggests potential adjustments to achieve their ultimate policy objectives. For nongovernmental organisations (NGOs), associations and society in general, our research provides evidence of the application of measures designed to make companies internalise pollution costs and the effectiveness of these measures in driving the transition to a low-carbon economy, as well as possible improvements in this regard.

TABLE 7 | Sobel–Goodman test (mediating effect).

	Coefficient	Bootstrap SE	*Z*	*P*>*z*	Normal base [95% CI]	
Indirect effect	0.000	0.000	0.890	0.374	−0.0001032	0.0002748
Direct effect	−0.009	0.002	−5.180	0.000	−0.0124191	−0.0055990
Total effect	−0.009	0.002	−5.130	0.000	−0.0123321	−0.0055144

Source: Authors.

6.2 | Limitations and Future Research

Two main aspects should be highlighted in reference to the limitations of the study. First, the difficulty in identifying the parent companies of all facilities forced us to exclude some observations. Second, the lack of data on certain variables, such as R&D expenditure (both overall and green R&D), for all companies in the sample forced us to use alternative measures. As noted earlier, these limitations result in a lack of homogeneity in the sample used in each analysis. Another limitation is that the research focused solely on publicly traded companies, given data availability restrictions. Therefore, the results should be generalised with caution.

Future research could expand the study of the impact of eco-innovation on GHG emissions by including alternative measures of R&D. The continued development of emissions trading markets and the expected improvements in corporate sustainability reporting transparency will provide new analytical contexts for examining the effectiveness of emissions trading systems in mitigating climate change and achieving global decarbonisation objectives.

Acknowledgements

The authors thank the Cátedra Finanzas Internacionales–Banco Santander of the University of Valencia for their support.

Conflicts of Interest

The authors declare no conflicts of interest.

Endnotes

[1] Beyond the EU-ETS, national or subnational emissions trading systems are currently operating or are under development in Canada, China, Japan, New Zealand, South Korea, Switzerland and the United States (EU Climate Action-European Union, https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/international-carbon-market_en, accessed 10 February 2025).

[2] EU Climate Action-European Union https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en, accessed 10 February 2025.

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