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The Impact of Product Environmental Innovation in Process Industries: Evidence from Innovation Efficiency and Performance

Yeongjun Kim [1,2], Jiyun Seong [3] and Changhee Kim [2,*]

1 College of Social Science, Hansung University, Seoul 02876, Republic of Korea; bkim@hansung.ac.kr
2 College of Business Administration, Incheon National University, Incheon 220212, Republic of Korea
3 Business School, Korea University, Seoul 02841, Republic of Korea; jy.jiyunseong@gmail.com
* Correspondence: ckim@inu.ac.kr; Tel.: +82-32-835-8734

Abstract

This study examines the heterogeneous effects of product environmental innovation on firm-level innovation efficiency and performance in process industries, with a focus on the chemical and electronics sectors. Following the Organisation for Economic Co-operation and Development (OECD)'s Oslo Manual, four types of product environmental innovation are considered: reducing energy use and emissions (RUE), reducing pollution (RP), promoting recycling (PR), and enhancing durability and extending product life (EDEL). Innovation efficiency is evaluated using the input-oriented Banker–Charnes–Cooper (BCC) Data Envelopment Analysis (DEA) model, and regression analyses are applied to test the effects of each innovation type on efficiency and sales outcomes. The results reveal that RUE and EDEL consistently enhance both efficiency and performance, whereas PR has a negative impact on performance, and RP shows no significant effect. These findings demonstrate that product environmental innovation is not a homogeneous construct but yields heterogeneous outcomes depending on type and industry context. The study contributes to the literature by jointly examining efficiency and performance outcomes and by overcoming the limitations of single-metric evaluations, and it provides practical implications by clarifying which innovation types deliver immediate value in business-to-consumer (B2C) markets and which are more relevant for business-to-business (B2B) settings.

Keywords: process industry; product environmental innovation; innovation efficiency; data envelopment analysis

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1. Introduction

Process industries, together with assembly-based industries, constitute a cornerstone of the manufacturing sector and account for a substantial share of production in developed countries [1]. In particular, chemical and electronic products make significant contributions to the national economies and are regarded as future growth engines [2]. These industries necessitate continuous innovation through research and development. At the same time, they are high energy- and resources-intensive, leading considerable greenhouse gas emissions and waste generation [3,4]. Therefore, environmental innovation has become indispensable in these industries, although it entails challenges such as resource constraints, institutional uncertainty, and short-term performance pressures [5,6]. Firms must therefore strategically decide which types of innovation to prioritize based on their organizational capabilities and goals [7].

Existing research on environmental innovation in process industries has primarily concentrated on process innovation, reflecting industry characteristics, conventional research paradigms, and corporate strategies. For example, the chemical industry—classified as a mature sector—emphasizes process innovation, which allows for cost reduction and productivity enhancement, over product innovation [8]. The electronics industry also relies heavily on production lines and facilities, while regulatory compliance has focused on pollutant management at the process stage, reinforcing a process-centered approach.

Moreover, the Cleaner Production paradigm has been widely adopted in the chemical industry, shaping the trajectory of process-centered environmental innovation research in both academia and practice [9]. In competitive market environments, firms prioritize cost reduction and risk management over differentiated product innovation [10]. However, the impact of process innovation is confined to internal efficiency and is often less visible to consumers and the market [11]. Consequently, its short-term contribution to market performance tends to be limited [12].

In contrast, product environmental innovation provides immediate, tangible benefits to consumers, such as the use of eco-friendly materials, energy savings, and ease of recycling. Such innovations can rapidly increase sales and market share by delivering recognizable value to customers [13]. Furthermore, product environmental innovation fosters differentiation and strengthens brand value, thereby facilitating early diffusion and competitive advantage [14]. In addition, it improves both financial and environmental performance, serving as a catalyst for long-term sustainability [15]. Therefore, product environmental innovation is not only essential for the environmental transition but also a strategic tool for enhancing market performance.

Despite this importance, many studies on process industries treat product environmental innovation as a single variable, often neglecting its diverse type—such as energy savings, pollution reduction, recycling promotion, and durability enhancement [16]. This oversimplified approach limits practical application for strategic decision-making. Likewise, many studies fail to account for innovation as a complex, interactive process that transforms multiple inputs into outputs, instead use only a single financial indicator, such as sales, to evaluate innovation performance [17].

To address these limitations, this study adopts the OECD's Oslo Manual framework to classify product environmental innovation into four types: reducing energy use and emissions (RUE), reducing pollution (RP), promoting recycling (PR), and enhancing durability and extending product life (EDEL). Focusing on chemical and electronics manufacturing industries, the analysis investigates the impact of each innovation type on both innovation performance and innovation efficiency at the firm level. Innovation efficiency is assessed using Data Envelopment Analysis (DEA), while tobit and multiple regression models are employed to examine the impact of each innovation type on performance and efficiency. This dual approach provides quantitative evidence on the role of product environmental innovation in process industries and offers practical insights for firms aiming to design effective and efficient innovation strategies.

The contributions of this study are twofold. First. It expands the literature by disaggregating product environmental innovations and evaluating their heterogeneous impacts using dual measures—innovation efficiency and sales performance—thereby addressing the limitations of single-metric evaluations. Second, it provides practical implications by demonstrating how the effectiveness of innovation types varies depending on industry characteristics, particularly the differences between business to business (B2B) and business to customer (B2C) markets.

Based on this framework, several working expectations are proposed. First, reducing energy use and emissions (RUE) is expected to enhance both innovation efficiency and performance by lowering costs and improving competitiveness. Second, reducing pollution (RP) is anticipated to support compliance and mitigate operational risks, although its short-term impact on market performance may be limited. Third, promoting recycling (PR) may impose design and cost constraints that reduce efficiency and negatively affect performance in the short term. Finally, enhancing durability and extending product life (EDEL) is expected to deliver immediate and visible benefits to both consumers and industrial customers, thereby improving efficiency and boosting performance.

Following Section 2 reviews the literature on product environmental innovation and innovation efficiency. Section 3 outlines the data and research model. Section 4 summarizes the analysis results. Section 5 discusses the findings, and Section 6 presents implications and future research directions.

2. Literature Review

2.1. Product Environmental Innovation

Product environmental innovation extends beyond conventional product development. It encompasses reducing carbon footprints and enhancing sustainability through waste management, emission reduction, and eco-design [18]. The OECD 2025 identifies four types of environmental benefits for end consumers: (1) energy savings and carbon emissions reduction, (2) pollution mitigation, (3) recycling promotion, and (4) durability enhancement [19].

The chemical and electronics industries differ in how these four types of innovations are implemented, reflecting the market structure, particularly, whether B2B or B2C-oriented. The chemical industry, as a B2B industry primarily supplying raw materials and intermediate goods, focuses on enhancing environmental benefits across the supply chain through materials innovation. By contrast, the electronics industry, with its hybrid B2B and B2C orientation, emphasizes environmental values directly perceptible to end consumers.

For energy-saving innovations, the chemical industry improves energy efficiency at the supply chain level through high-efficiency catalysts [20], bio-based raw materials [3], and advanced insulating materials, primarily benefiting B2B customers. Conversely, the electronics industry focuses on energy savings and carbon reduction during consumer use, such as low-power semiconductors [21] and energy-efficient appliances [22].

Differences also emerge in pollution-reducing innovations. The chemical industry reduces emissions at the process stage for B2B customers via material substitutions, including low-VOC materials [23], heavy metal-free colorants [24], and phosphate-free detergents [25]. The electronics industry, on the other hand, eliminates hazardous substances at the component and process levels through measures such as RoHS compliance [26], halogen-free flame retardants, and eco-friendly detergents [27]. These effects not only improve the supply chain environmental performance but also increase consumer awareness of safety.

In recycling-promoting innovation, the chemical industry focuses on material recyclability, such as biodegradable materials and single-material plastics [28], thereby supporting B2B customers' resource circulation strategies. The electronics industry, in contrast, has established a consumer-level circular system through modular design [29], recycled aluminum [30], and e-waste recovery [31].

Finally, in durability-enhancing innovation, the chemical industry extends the lifespan of industrial goods and components through heat- and corrosion-resistant coatings [32] and polymer materials [33], thus improving supply chain sustainability. The electronics industry emphasizes product durability that is directly perceptible to consumers, through waterproof and dustproof smartphones [34], extended battery life [35], and long-lasting displays [36].

2.2. Innovation Efficiency

Innovation is not a linear relationship between inputs and outputs; identical inputs do not necessarily yield identical outputs [17]. Accordingly, innovation should be evaluated in terms of innovation efficiency, defined as the ability to transform innovation inputs into innovation outputs [7].

Two widely applied methods for evaluating efficiency are Stochastic Frontier Analysis (SFA) and DEA. These two methods differ in both assumptions and approaches. SFA estimates efficiency statistically by assuming a specifying functional form, such as a production function or cost function. By contrast, DEA is a nonparametric method based on linear programming (LP). Unlike SFA, it accommodates multiple input and output variables simultaneously and does not require prior functional specification. Given these advantages, DEA has been widely employed in efficiency research across various industries, including manufacturing [17].

Table 1 summarizes studies evaluating the innovation efficiency of manufacturing firms using DEA. In general, DEA models for measuring innovation efficiency adopt the number of research and development (R&D) personnel and R&D expenses (or innovation activity expenses) as input variables, while Innovation sales (sales of innovative products) serve as output variables.

Table 1. Innovation efficiency study using DEA.

Researcher	DMUs	Input Variable	Output Variable	Method
Shin et al. [37]	743 medical device companies	R&D expenditure, Employees	Sales	BCC DEA
Zhang et al. [38]	45 new energy vehicle companies	R&D employee, R&D expenditure, Sales expenses	Patent, Intangible assets, Operating income	Slack-based DEA, Meta-frontier model
Shin et al. [39]	902 manufacturing companies	R&D employee, Innovation cost	Innovation sales	Bootstrapped DEA
Shin et al. [8]	64 chemical companies	R&D employee, Innovation cost	Sales	Bootstrapped DEA
Park [40]	1778 manufacturing companies	R&D employee, R&D expenditure,	Innovation sales	BCC DEA

Taken together, the literature indicates that product environmental innovation varies across industries, with B2B- and B2C-oriented contexts shaping its types and outcomes. Moreover, prior studies highlight the need to evaluate innovation in terms of efficiency rather than relying solely on sales-based indicators. Therefore, this study investigates the heterogeneous effects of four types of product environmental innovation on both innovation efficiency and performance in the chemical and electronics industries. To achieve this aim, the following section describes the data, variables, and analytical framework employed in this study.

3. Methodology

3.1. Data Envelopment Analysis (DEA) Approach

DEA is a non-parametric method based on LP that measures the relative efficiency of decision-making units (DMUs) [41]. In DEA, efficient firms establish the efficient frontier, and the efficiency of other firms is measured relative to their distance from this frontier. Firms on the efficient frontier have an efficiency score of 1, whereas those located outside the frontier score less than 1 and are considered inefficient.

Two standard DEA models are widely employed. The Charnes-Cooper-Rhodes (CCR) model assesses overall technical efficiency under the assumption of constant returns to scale (CRS). In contrast, the BCC model allows for variable returns to scale (VRS), enabling the decomposition of technical efficiency into scale efficiency and pure technical efficiency. In other words, the BCC model accounts for economies of scale. DEA can also be categorized as input-oriented and output-oriented, depending on whether firms are assumed to control inputs or outputs. As output such as innovation sales is generally less controllable by firms than inputs, this study uses an input-oriented BCC model to evaluate innovation efficiency.

Because DEA efficiency scores are bounded between 0 and 1 (censored distribution), the ordinary least squares (OLS) regression may result in biased estimates. To address this issue, maximum-likelihood (ML) based tobit regression analysis is commonly employed in DEA research. The tobit regression is designed to account for the censored problem, where the dependent variable is observed only within a restricted range, and efficiently estimates coefficients under such conditions [42].

3.2. Data Collection and Variable Definition

This study employs data from the 2022 Korea Innovation Survey (KIS) manufacturing sector, conducted by the Science and Technology Policy Institute (STEPI). The sample comprises 283 firms in the two process industries: 140 companies in the "manufacturing of chemicals and chemical products; excluding pharmaceuticals" sector, and 143 companies in the "manufacturing of electronic components, computers, video, audio, and communication equipment". The KIS follows Oslo Manual, the OECD's guideline for innovation survey, and encompasses information on general corporate status, performance, and overall innovation activities.

Input and output variables for DEA are selected based on prior literature. The input variables are the number of R&D personnel and innovation costs, while the output variable is innovation sales. The number of R&D personnel is calculated by multiplying the number of full-time employees by the share of staff engaged in R&D. Innovation sales are calculated by multiplying total sales by the share of sales derived from innovative products. R&D personnel represent the human resources devoted in innovation activities, whereas innovation costs reflect financial investment in technological development [43,44]. Innovation sales represent the final output of innovation and demonstrate the added value created by firms through innovation [45].

The independent variables in the tobit and multiple regression analyses are four types of product environmental innovation: 1. Reduce energy use and emissions (RUE); 2. Reduce air, water, soil, and noise pollution (RP); 3. Promote post-use recycling (PR); and 4. Enhance durability and extend product life (EDEL). Each variable is binary indicator, taking a value of 1 if the firm has implemented the innovation and 0 otherwise. This classification, adopted from the OECD's Oslo manual, reflects internationally accepted innovation measurement standards and facilitates systematically and comparatively analysis of product environmental innovation.

The control variables are firm age and firm size. Firm age is calculated as the difference between the firm's founding year and survey year. Firm size is measured by the total number of employees. Both variables are transformed into natural logarithms for analysis. Firm age and Firm size are widely adopted control variables. Firm age reflects accumulated knowledge and learning effects that may influence performance [46], while firm size explains differences in R&D resources and innovation capabilities [47]. Controlling these variables provides more accurate estimation of the effects of product environmental innovation.

Table 2 reports the descriptive statistics of all variables. Innovation sales, as the output variable, indicate firms' ability to generate revenues from innovative products. R&D personnel and innovation costs capture human and financial inputs to innovation. Firm age and size control for organizational differences in learning and resource capacity, while the four environmental innovation variables capture specific strategies adopted by firms. This classification clarifies the conceptual role of each variable and underscores their importance in analyzing the efficiency and performance of environmental innovation.

Table 2. Descriptive statistics of the entire industry.

	Variable	Max	Min	Mean	St.dev
Output	Innovation sales	9,590,000.000	11.000	204,651.149	811,873.116
Input	R&D personnel	2202.000	1.000	54.890	170.497
	Innovation expenditure	637,249.000	20.000	8579.890	43,789.490
Control	ln (Firm age)	4.331	1.099	3.068	0.637
	ln (Employees)	9.358	2.303	5.132	1.407
Dependent	RUE	1.000	0.000	0.512	0.500
	RP	1.000	0.000	0.473	0.499
	PR	1.000	0.000	0.456	0.498
	EDEL	1.000	0.000	0.558	0.497

Units: Innovation sales (million KRW); R&D personnel (persons); Innovation expenditure (million KRW); ln (Firm age) (years); ln (Employees) (persons).

3.3. Research Model

The purpose of this study is to investigate the effects of product environmental innovation in the process industry. To achieve this, the analysis is conducted in three steps, as shown in Figure 1.

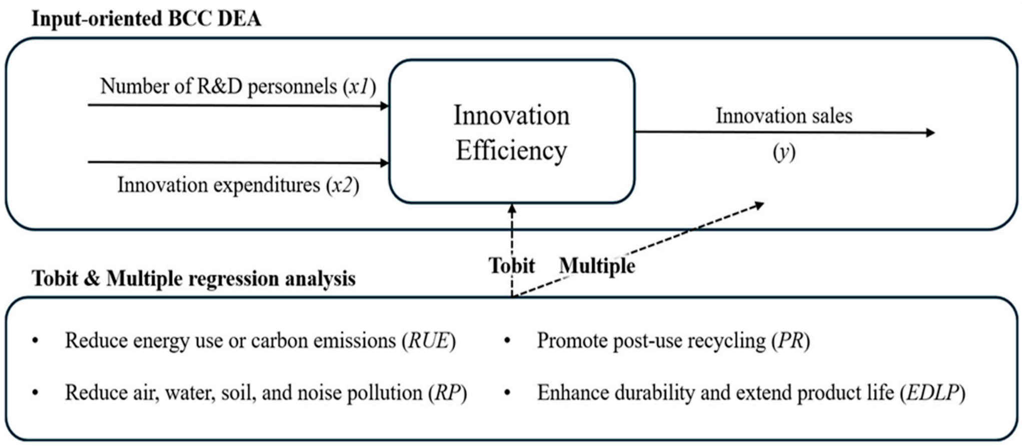

Figure 1. Research Model.

First, the innovation efficiency of 283 firms is evaluated using the input-oriented BCC DEA model, where inputs are R&D personnel and innovation costs, and the output variable is innovation sales. The resulting efficiency coefficients range between 0 and 1; higher scores indicate that firms are closer to the efficient frontier and are more effective in transforming innovation inputs into outputs, while lower scores imply inefficiency and resource misallocation.

Second, Tobit regression is applied to estimate the effects of the four types of product environmental innovation (RUE, RP, PR, and EDEL) on innovation efficiency. Tobit estimation is appropriate because DEA efficiency scores are censored between 0 and 1 and thus cannot be analyzed accurately using OLS regression [42].

Third, multiple regression analysis is employed to test the effects of the four innovation types on innovation performance, measured by innovation sales. To ensure robustness, separate analyses are conducted for the chemical and electronics industries, which allows comparison between B2B- and B2C-oriented contexts and clarifies industry-specific heterogeneity.

By combining DEA with regression analyses, this research model integrates efficiency and performance perspectives, offering a comprehensive framework for evaluating the role of product environmental innovation in process industries. The efficiency coefficient obtained from the DEA is not interpreted as a direct benchmarking tool for individual firms but rather serves as an intermediate analytical construct. In this study, it functions as the dependent variable in regression analysis to assess how different types of product environmental innovation influence firms' ability to transform innovation resources into outcomes. This approach ensures that the efficiency measure provides meaningful insights into resource utilization, while the primary interpretation of findings is derived from the regression results.

4. Results Analysis

4.1. Regression Analysis Results for the Entire Industry

Table 3 presents the regression results for the entire process industry. PR (Promote post-use recycling) was found to have a negative impact on innovation sales at a significance level of 0.01. This result is consistent with the working expectation that PR may reduce short-term performance because consumers in B2C markets have difficulty perceiving long-term environmental benefits, such as recyclability, at the point of purchase. Instead, factors such as convenience, performance, and price typically play a more important role in consumers' purchasing decisions. Emphasizing recyclability may also impose design constraints, user inconvenience, and higher prices, which can lead to lower sales [48,49]. In contrast, in B2B markets, industrial customers tend to value recyclability as a means of fulfilling environmental responsibilities, which can help improve compliance with environmental regulations and sustainability. Therefore, the impact of PR may vary between B2C and B2B markets.

Table 3. Results of Regression Analysis of the Entire Industry.

Model	**Model 1 (Tobit)**		**Model 2 (OLS)**	
Dependent Variable	**Innovation Efficiency**		**Innovation Efficiency**	
Independent Variable	**Coefficient**	**Std. Error**	**Coefficient**	**Std. Error**
RUE	0.216	0.232	0.531	0.330
RP	−0.360	0.263	0.145	0.357
PR	−0.012	0.266	−1.449 ***	0.365
EDEL	0.413 **	0.174	1.829 ***	0.255
Firm age	−0.075	0.096	−0.141	0.145
Firm size	−0.289	0.044	1.329 ***	0.065
Log-likelihood	176.155			
Wald-statistics	114.595			
R^2			0.696	
F-statistics			93.299 ***	

** $p < 0.05$, *** $p < 0.01$.

Conversely, EDEL (Enhance durability and extend product life) demonstrated a positive impact on both innovation sales and innovation efficiency across B2C and B2B markets. This result aligns with the working expectation that EDEL provides immediate value, by offering both cost savings and psychological satisfaction [50,51]. In B2B markets, it contributes to long-term cost reduction and operational efficiency, thereby increasing sales and improving efficiency.

4.2. Regression Analysis Results for the Chemical Industry

Table 4 reports the regression results for the chemical industry. RUE (Reduce energy use and emissions) had a positive impact on both innovation sales and innovation efficiency at a significance level of 0.01. This result is consistent with the working expectation that RUE directly improve competitiveness by lowering costs and facilitating compliance with environmental regulations. For industrial customers in B2B markets, the benefits of energy savings and carbon reductions are directly experienced, which also enhances ESG ratings. Such benefits not only improve purchasing attractiveness but also strengthen performance relative to its inputs, positively influencing efficiency.

Table 4. Results of Regression Analysis of Industry (KSIC 20).

Model	Model 1 (Tobit)		Model 2 (OLS)	
Dependent Variable	Innovation Efficiency		Innovation Efficiency	
Independent Variable	Coefficient	Std. Error	Coefficient	Std. Error
RUE	0.856 ***	0.308	1.516 ***	0.428
RP	−0.165	0.341	−0.014	0.474
PR	−0.024	0.434	−1.289 **	0.604
EDEL	−0.097	0.389	1.353 **	0.541
Firm age	−0.152	0.123	0.026	0.171
Firm size	−0.190 ***	0.064	1.440 ***	0.089
Log-likelihood	31.371			
Wald-statistics	26.098			
R^2			0.750	
F-statistics			70.335 ***	

** $p < 0.05$, *** $p < 0.01$.

In contrast, PR (Promote post-use recycling) exhibited a negative impact on innovation sales at a significance level of 0.05. This finding is consistent with the hypothesis that PR is difficult for end consumers to perceive directly, while industrial customers associate recycled materials with potential quality degradation or increased costs, perceptions that tend to negatively influence purchasing decisions in the B2B market.

Finally, EDEL (Enhance durability and extend product life) showed a positive impact on innovation sales at a significance level of 0.05. This outcome is in line with the working expectation that durable products such as advanced coatings or materials can yield to long-term cost savings and operational efficiency for industrial customers, making durability a key determinant of purchase decisions in the B2B market.

4.3. Regression Analysis Results for the Electronic Industry

Table 5 presents the regression results for the electronics industry. RUE (Reduce energy use and emissions) was found to have a positive effect on innovation sales at a significance level of 0.05, but a negative effect on innovation efficiency at a significance level of 0.01. This partly aligns with the working expectation: in the B2C market, energy-saving products enhance sales by offering tangible benefits such as lower electricity bills and a reduced carbon footprint, which increase purchase appeal. However, in the B2B market, implementing such innovation often requires additional R&D investment and costly materials, which reduce efficiency. Consequently, the short-term financial burden can finder innovation efficiency from the firm's perspective.

PR (Promote Post-Use Recycling) produced a negative effect on innovation sales at a significance level of 0.01. This result is consistent with the working expectation that recyclability provides limited perceived benefits. In the B2C market, consumers of electronic products prioritize performance, design, and convenience as the primary criteria for purchase decisions [52,53]. Moreover, recyclability may impose product design restrictions or be perceived as an additional cost, reducing sales appeal. By contrast, in the B2B market, recyclability may be positively evaluated by companies that prioritize environmental regulations compliance and sustainability. For industrial customers, environmental innovation contributes to brand value and social responsibility, thereby yielding positive impact in the B2B context.

Table 5. Results of Regression Analysis of Industry (KSIC 26).

Model	Model 1 (Tobit)		Model 2 (OLS)	
Dependent Variable	Innovation Efficiency		Innovation Efficiency	
Independent Variable	Coefficient	Std. Error	Coefficient	Std. Error
RUE	−1.062 ***	0.370	−0.978 **	0.480
RP	0.303	0.402	0.890	0.503
PR	−0.026	0.412	−1.264 ***	0.434
EDEL	0.905 ***	0.273	1.833 ***	0.266
Firm age	−0.030	0.200	−0.333	0.188
Firm size	0.000	0.063	1.130 ***	0.076
Log-likelihood	59.606			
Wald-statistics	20.568			
R^2			0.663	
F-statistics			47.458 ***	

** $p < 0.05$, *** $p < 0.01$.

Finally, EDEL (Enhance durability and extend product life) exhibited impact on both innovation revenue and innovation efficiency at the 0.01 significance level. This finding reflects the working expectation that durability delivers immediate and visible benefit. In the B2C market, attributes such as fewer failures and longer service life extend beyond physical performance to provide both economic and psychological benefits [54,55]. These attributes strengthen purchase appeal, leading to increased sales and efficiency. In B2B markets, durability likewise constitutes an important factor. Industrial customers benefit from cost reduction and long-term efficiency gains through durable products, which positively affects both sales growth and efficiency.

5. Discussion

The empirical findings of this study highlight that the effects of product environmental innovation are not uniform but vary depending on the type of innovation and industry context. This heterogeneity provides important implications for both theory and practice.

First, RUE (Reduce energy use and emissions) showed a positive effect on both innovation efficiency and performance. This finding is consistent with the working expectation that energy-saving and emission-reducing innovations directly contribute to resource optimization and improved competitiveness, particularly in energy-intensive industries. Such outcomes are also in line with earlier studies that emphasize the dual role of energy-related innovations in reducing costs and enhancing environmental compliance [48].

Second, RP (Reduce pollution) did not show a significant effect on either efficiency or performance, suggesting that compliance-driven innovations may contribute to long-term sustainability but exert limited short-term impact. This result reflects the working expectation that pollution-reducing innovations may enhance regulatory compliance without necessarily delivering immediate market advantages. It also resonates with prior research that notes the difficulty of linking pollution-reduction efforts to tangible improvements in sales or efficiency [49].

Third, PR (Promote post-use recycling) revealed a negative effect on innovation performance. This result is consistent with the working expectation that recycling-oriented innovation imposes additional design and cost burdens, which are less valued in B2C markets where consumers prioritize price, design, and convenience [50]. In B2B contexts as well, recycled materials may be associated with quality concerns or higher costs, limiting their attractiveness to industrial buyers. These findings align with earlier studies reporting that recycling-focused innovations can be costly and their benefits less visible in the short term [51].

Finally, EDEL (Enhance durability and extend product life) consistently exhibited a positive effect on both innovation efficiency and performance. This result supports the working expectation that durability-enhancing innovations provide immediate and visible benefits. In B2C markets, durability reduces replacement costs and offers psychological satisfaction, while in B2B contexts it generates long-term cost savings and operational stability. This finding resonates with the concept of "functional value" in consumption value theory, which posits that products delivering direct economic and psychological benefits are more likely to improve market performance [56]. It is also consistent with prior studies highlighting durability as a key determinant in both consumer and industrial markets [52,53].

Overall, these results demonstrate that the impacts of environmental innovation cannot be generalized as uniformly positive. Instead, they depend on both the nature of the innovation and the industry in which it is applied. This study extends the literature by showing that RUE and EDEL deliver consistent benefits, while PR may reduce performance and RP exerts little short-term influence.

Nevertheless, the generalizability of these results is limited. The analysis was confined to process industries, specifically the chemical and electronics sectors, which differ from other manufacturing industries in technological trajectory and market orientation. As such, caution is required when applying these findings to other contexts. Future research should extend this analysis to assembly-based industries or service sectors to verify whether the heterogeneous effects of product environmental innovation observed here are more broadly applicable.

6. Conclusions

This study investigated the heterogeneous effects of four types of product environmental innovation—reducing energy use and emissions (RUE), reducing pollution (RP), promoting recycling (PR), and enhancing durability and extending product life (EDEL)—on firm-level efficiency and performance in process industries. Using DEA and regression analysis, the study analyzed 283 firms in the chemical and electronics sectors.

The results show that RUE and EDEL consistently enhance both innovation efficiency and performance, confirming that environmental innovations offering tangible and meaningful benefits are more likely to generate market advantages [56]. By contrast, PR negatively affects performance and does not improve efficiency, while RP has no significant effect. These findings underscore that environmental innovation is not a homogeneous construct but produces heterogeneous outcomes depending on type and industry context [57].

The study contributes to the literature by demonstrating these differentiated effects and by showing the importance of evaluating efficiency and performance together rather than relying on a single measure. Practically, the findings suggest that firms should prioritize RUE and EDEL when designing innovation strategies, while recognizing the limited short-term value of RP and PR.

Despite these implications, the generalizability of the results is limited to process industries, specifically chemicals and electronics. As highlighted in prior work, sectoral and regulatory contexts strongly shape the effects of environmental innovation [58]. Future research should extend the analysis to other industries and innovation types to validate and broaden these conclusions.

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