Product Innovations toward a Circular Economy: A Survey-Based Analysis of Slovak Manufacturing Firms

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ABSTRACT

Purpose: This paper investigates the adoption of product eco-innovations among Slovak manufacturing firms in the context of circular economy (CE) transition and assesses their relationship with industry sectors and company size.

Methodology/Approach: A quantitative survey of 101 Slovak manufacturing firms was analysed using chi-square tests, Cramér's V, and Spearman correlations to explore links between eco-innovation adoption and firm characteristics.

Findings: Firm size significantly relates to general product eco-innovation, but not to five of six specific eco-innovations (health impact, energy use, lifespan, pollution, recycling). Only easier maintenance or upgrading shows this link. No significant link exists between industry sectors and product eco-innovation, although sectoral differences are evident in specific eco-innovations. Specific eco-innovations, such as those that reduce pollution and increase product longevity, often co-occur.

Research Limitation/Implication: The main limitation lies in the national scope and single-method approach.

Originality/Value of paper: This paper adds to the limited empirical research on product eco-innovation in Central Europe by offering novel insights into sectoral and size-based patterns aligned with CE goals.

Category: Research paper

Keywords: product innovation; circular economy; manufacturing; company, Slovakia

Research Areas: Management of Technology and Innovation; Quality by Sustainability

1 INTRODUCTION

In recent decades, environmental sustainability has emerged as one of the most pressing global challenges, prompting industries worldwide to reconsider their production processes and product designs. Manufacturing companies, as major contributors to resource consumption, emissions, and waste generation, face increasing pressure from governments, consumers, and investors to adopt more sustainable practices. Within this context, product innovation has been identified as a critical driver for achieving environmental improvements (Fleith de Medeiros *et al.*, 2022).

Product innovations with an environmental focus, often termed eco-innovations, can deliver multiple benefits, including biodegradable material selection, minimized pollution, reduced energy consumption, enhanced recyclability, and extended product lifespan. Such innovations not only contribute to environmental protection but also can bring substantial product differentiation and competitiveness for these products (Dangelico and Pujari, 2010) to better meet the growing demand for greener products and comply with tightening environmental regulations (Ghosh, Shah and Swami, 2020; Horbach, Rammer and Rennings, 2012). Furthermore, eco-innovations support the transition towards circular economy models, which emphasize resource efficiency and waste reduction, thereby fostering long-term sustainability in manufacturing (Ghisellini, Cialani and Ulgiati, 2016; Ellen MacArthur Foundation, 2025).

Slovakia's manufacturing sector plays a vital role in the national economy, representing a significant share of employment and industrial output. Despite its economic importance, empirical research examining the integration of environmental considerations into product innovation in Slovak manufacturing is sparse. Existing studies tend to focus on broader innovation trends (SOVA digital, 2017; Urbaníková *et al.*, 2020; Korcsmaros *et al.*, 2024) or eco-innovation (Vinczeová, Klement and Klementová, 2024; Domaracká *et al.*, 2025), only a few with a focus on product eco-innovation (Vicianová *et al.*, 2017; Loučanová, Olšiaková and Štofková, 2022) (while the latter only from the customers' perspective). These gaps limit the understanding of how Slovak companies are responding to sustainability challenges through their product eco-innovation activities and what types of environmental benefits of new or improved products they prioritise. Above this, the paper uncovers not only product eco-innovation in general, but also delves into the types of product eco-innovations, with a special focus on environmental improvements that support the circular economy.

The paper also reacted to the more general gap that is specifically evident in research of sectoral differences in product eco-innovation adoption, where we could find only a few studies (e.g. Marin and Lotti, 2017; Fichter and Clausen, 2021; Biscione *et al.*, 2022) but not always covering all sub-sectors of the manufacturing industry, as defined by NACE (10-34). Additionally, Bal-Domańska, Stańczyk and Szewczyk (2025), based on research of Polish industrial firms, suggested that future studies should investigate how different industrial sectors respond to Pressure, Requirements, Reputation, and Incentives in the context of eco-innovation implementation. They argued that each sector has unique regulatory requirements, competitive dynamics, and technological or financial resource availability.

This study aims to fill these gaps by investigating the extent to which Slovak manufacturing firms have introduced environmentally improved products since 2019. Specifically, it explores the types of environmental improvements associated with new or improved products and analyses how these patterns vary across different industry sectors and company sizes. The research adopts a quantitative approach, surveying a representative sample of manufacturing companies and applying statistical methods to uncover significant relationships between industry, size and product eco-innovation.

The structure of the paper is as follows. After the introduction and literature review, the Materials and Methods section outlines the sample, data collection, questionnaire design, key variables, and analysis techniques. The Results section presents key findings, including types and adoption of environmental improvements in products and their relationship to industry and size characteristics. This is followed by the Discussion and Conclusions, which summarize the main insights.

2 LITERATURE REVIEW

Product Eco Innovation and the Circular Economy

The transition from a linear economy model towards a Circular Economy (CE) represents a profound paradigm shift in how societies and industries relate to natural resources and environmental sustainability. As defined by Prieto-Sandoval, Jaca and Ormazabal (2018), the CE is "an economic system that represents a change of paradigm in the way that human society is interrelated with nature and aims to prevent the depletion of resources, close energy and materials loops, and facilitate sustainable development through its implementation at the micro (enterprises and consumers), meso (economic agents integrated in symbiosis) and macro (city, regions and governments) levels." The CE model is based on three interrelated principles: (1) preserving and enhancing natural capital by controlling finite stocks and balancing flows and renewable resource, (2) optimizing resource yields through product utility and longevity and (3) fostering system effectiveness by eliminating negative externalities from the outset (Suchek *et al.*, 2021).

Eco-innovation (EI) is a key enabler in the transition to CE. For instance, Maldonado-Guzmán, Garza-Reyes and Pinzón-Castro (2020) confirm that EI activities in the Mexican automotive sector strongly influence CE implementation. According to Prieto-Sandoval, Jaca and Ormazabal (2018), eight types of EIs facilitate CE implementation: business model, network, organizational structure, process, product, service, market, and client involvement. Among these, product eco-innovations are particularly emphasized in cleaner production strategies and policies such as the Integrated Product Policy (IPP) promoted by the European Commission since 2001. IPP aims at supporting the development of environmental product innovations to minimize environmental impacts throughout a product's life cycle and is aligned with the increasing legal and market-driven pressures on manufacturing sectors to design sustainable products (European Commission, 2001; Maxwell and van der Vorst, 2003).

It appears that regulations play a crucial role in driving eco-innovations in products. For example, European Eco-design Directive has already yielded energy efficiency improvements in some products (European Commission, 2012). In addition, Horbach, Rammer and Rennings (2012) noted that firms recognise the high importance of future regulations for all environmental product innovations.

In addition to regulations, green demand also plays a role in promoting product innovations in the recycling and post-use phases (Cainelli, D'Amato and Mazzanti, 2020)or the adoption of bioplastic innovations (Confente, Scarpi and Russo, 2020).

Interestingly, environmental management systems do not play an essential role in environmental product innovations (Horbach, Rammer and Rennings, 2012). Still, according to Bocken *et al.* (2016), product innovation for circularity (such as designing goods with longer lifespans and extensions to product lifespans through service cycles (e.g. repair and remanufacture)) closely aligns with business model innovation.

If we look at the outcomes of the product eco-innovations for the firm, Rennings (2012) emphasise that eco-innovations (including product innovations) lead to measurable reductions in environmental burdens. According to their study, the economic outcomes of eco-innovations remain nuanced. For example, while energy-saving products can increase turnover, improvements in recyclability may reduce it due to higher internal costs. Other evidence of economic outcomes is provided by Vokoun and Jílková (2020), who show that product EI in Czech firms leads to increased sales.

In summary, the CE provides a comprehensive framework for sustainable transformation, where product eco-innovation plays a crucial role. In this context, the primary focus of this paper is to investigate circular-oriented product innovation, which prioritises durability, reparability and recyclability, aligning with the CE on resource efficiency and waste reduction (Perotti *et al.*, 2025).

3 MATERIALS AND METHODS

This section describes the research methodology employed to examine the eco-innovations of products in Slovak manufacturing companies. It outlines the sampling approach, data collection procedures, questionnaire structure, key variables, and analytical methods used to address the study's objectives.

3.1 Sample and Data Collection

This study focuses on Slovak manufacturing companies and examines the emergence of environmental improvements in new or significantly enhanced products. The total population comprises approximately 2,500 manufacturing firms in Slovakia (NACE 10–33) with 20 or more employees, as per publicly available data from FINSTAT. A stratified random sampling method was used to ensure representation across company size, region, and sector.

The survey was distributed online and via standard postal services in 2022 to relevant company representatives. A total of 102 companies completed the questionnaire. After data cleaning and validation, 101 companies provided valid responses and were included in the final analytical sample.

3.2 Sample Description

Table 1 provides an overview of the surveyed enterprises' structure, classified by industry and enterprise size. In terms of industry representation, the mechanical engineering sector dominates the sample, accounting for 29.70% of all participating enterprises (30 out of 101), followed by the food industry with 18.81% (19 enterprises).

Regarding enterprise size, the sample is predominantly composed of medium-sized enterprises, which constitute 51.49% of the total sample (52 enterprises). Small enterprises account for 28.71% (29 enterprises), while large enterprises represent 19.80% (20 enterprises).

Table 1 – Structure of the sample by industry sector and size

Enterprises by Industry	**Count**	**Share of Total Enterprise**
Mechanical engineering	30	29.70%
Food industry	19	18.81%
Electrical engineering	8	7.92%
Chemical	8	7.92%
Woodworking	7	6.93%
Metallurgical	6	5.94%
Automotive	5	4.95%
Light industry	3	2.97%
Construction	3	2.97%
Pharmaceutical	3	2.97%
Textile	3	2.97%
Energy	1	0.99%
Medical devices	1	0.99%
Printing industry	1	0.99%
Rubber industry	1	0.99%
Services	1	0.99%
Paper Industry	1	0.99%
Enterprises by Size	**Count**	**Share of Total Enterprise**

Enterprises by Industry	Count	Share of Total Enterprise
Small enterprise (< 50 employees)	29	28.71%
Medium enterprise (50–249 employees)	52	51.49%
Large enterprise (>= 250 employees)	20	19.80%

3.3 Questionnaire Design

The structured questionnaire included several questions on innovation and the environmental impact of new or significantly improved products. This paper focuses on a specific subset of questions related to product innovation and environmental outcomes.

The primary screening question was:

"Did your company introduce products since 2019 that were new to your site or featured significant technical improvements?"

If respondents answered "Yes," a follow-up question was posed:

"Did these new or improved products lead to environmental improvements during use or disposal?"

Companies that responded positively to this follow-up were then asked to select one or more specific types of environmental improvements in their new products.

3.4 Key Variables

The key variables analysed in this study include:

- Industry Classification: Each company was classified into a relevant manufacturing sector (e.g., mechanical, chemical, food, electrical, etc.).
- Product Innovation Status: Whether the company has introduced new or significantly improved products since 2019.
- Product Eco-Innovation Status: Whether these products contributed to positive environmental outcomes during use or disposal.
- Types of Product Eco-Innovation: Companies indicating a positive environmental impact could select from the following predefined categories:
    - Reduction of health risks during product use,
    - Reduced energy consumption during product use,
    - Easier maintenance or upgrading/modernisation,
    - Extended product lifespan,
    - Reduction of environmental pollution during use,
    - Improved properties for recycling, take-back, or disposal.

These variables were coded as binary (1 = selected, 0 = not selected) and served as the foundation for the statistical analysis.

3.5 Data Analysis Techniques

The analysis of collected data employed descriptive and selected inferential statistical methods to explore the relationships between industry sectors, firm size and the adoption of product eco-innovations.

Descriptive statistics summarized the frequency and proportion of responses for each variable, where the relative frequency p was calculated as:

$$p = \frac{n_1}{n} \tag{1}$$

where n_1 is the number of cases where the characteristic is present (coded as 1), and n is the total sample size (Agresti, 2007).

Contingency tables were constructed to examine the joint distribution of categorical variables, displaying the observed frequencies for each category combination (Pallant, 2020).

The Chi-square (χ^2) test of independence was used to assess statistically significant associations between categorical variables, by comparing observed (O_{ij}) and expected (E_{ij}) frequencies within the contingency tables. The test statistic was computed as

$$\chi^2 = \sum_{i=1}^{r} \sum_{j=1}^{c} \frac{(O_{ij} - E_{ij})^2}{E_{ij}}, \tag{2}$$

where:

- r = number of rows (categories of variable 1)
- c = number of columns (categories of variable 2)
- Oij = observed frequency in cell (i, j)
- Eij = expected frequency in cell (i, j), calculated as:

$$E_{ij} = \frac{(Rox\ Total_i) * (Column\ Total_j)}{n}, \tag{3}$$

The degrees of freedom (df) were given by:

$$df = (r-1) * (c-1). \tag{4}$$

A p-value is obtained by comparing the calculated χ^2 statistic to the chi-square distribution with the corresponding degrees of freedom. A p-value less than the significance threshold (usually 0.05) indicates that the variables are not independent, suggesting a statistically significant association (Agresti, 2007; Field, 2024).

To quantify the strength of significant associations, Cramér's V was calculated:

$$V = \sqrt{\frac{\chi^2}{n(k-1)}}, \tag{5}$$

where:

- χ^2 is the chi-square test statistic,
- n is the total number of observations,
- k is the smaller of the number of rows or columns in the contingency table (McHugh, 2013).

Cramér's V ranges from 0 (no association) to 1 (perfect association), with conventional interpretations as follows (Reinard, 2006; Akoglu, 2018):

- 0 to 0.1: negligible association,
- 0.1 to 0.3: weak association,
- 0.3 to 0.5: moderate association,
- 0.5: strong association.

In addition, to assess monotonic relationships between ordinal or ranked variables, Spearman's rank-order correlation coefficient (ρ) was employed. Spearman's ρ measures the strength and direction of association between two ranked variables and is calculated as:

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \tag{6}$$

where:

- d_i is the difference between the ranks of corresponding values,
- n is the number of paired observations.

The value of Spearman's ρ ranges from -1 (perfect negative correlation) to +1 (perfect positive correlation), with 0 indicating no correlation. This non-parametric method is suitable for ordinal data or when the assumptions of Pearson correlation are violated (Field, 2024).

Statistical analyses were performed using IBM SPSS Statistics (version 29) and Microsoft Excel. Contingency tables and the chi-square test, along with associated effect size calculations, were conducted primarily in SPSS, ensuring accurate computation and hypothesis testing.

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4 RESULTS

This section presents the key findings derived from the analysis of the survey data. It provides an assessment of the extent of product innovation and eco-innovation adoption, as well as a more detailed examination of specific types of eco-innovation in new or improved products. Furthermore, a statistical relationship is identified between industry sectors, firm size, and eco-innovations in products.

4.1 Descriptive Statistics of Innovations and Eco-Innovations of Products

Out of the total sample of 101 enterprises, 60 companies (59.41%) reported no adoption of product improvements, while 41 companies (40.59%) introduced new or improved products. Among the 41 innovators, 21 companies (20.79% of the total sample; 51.22% of innovators) stated that their product innovations had a positive environmental impact, for example, through lower energy consumption, reduced material use, or improved recyclability. Respondents were allowed to select one or more from six environmental improvement categories (see Figure 1) that best described the type of improvement their innovations contributed to.

Figure 1 illustrates the distribution of the reported types of environmental improvements achieved during the product use phase by the 21 enterprises that introduced eco-innovations. The most frequently mentioned improvement was "Reduced energy consumption during product use", reported by 13 companies. This indicates a predominant focus on energy efficiency among environmentally oriented innovations. The second most common improvement was the "Reduction of environmental pollution during use" (8 companies), followed by "Improved properties for recycling, take-back, or disposal" and "Easier maintenance or upgrading/modernisation", both reported by 6 companies, and "Extended product lifespan" was selected by 5 enterprises. The "Reduction of health risks during product use" was the least frequently reported improvement, with only 3 mentions.

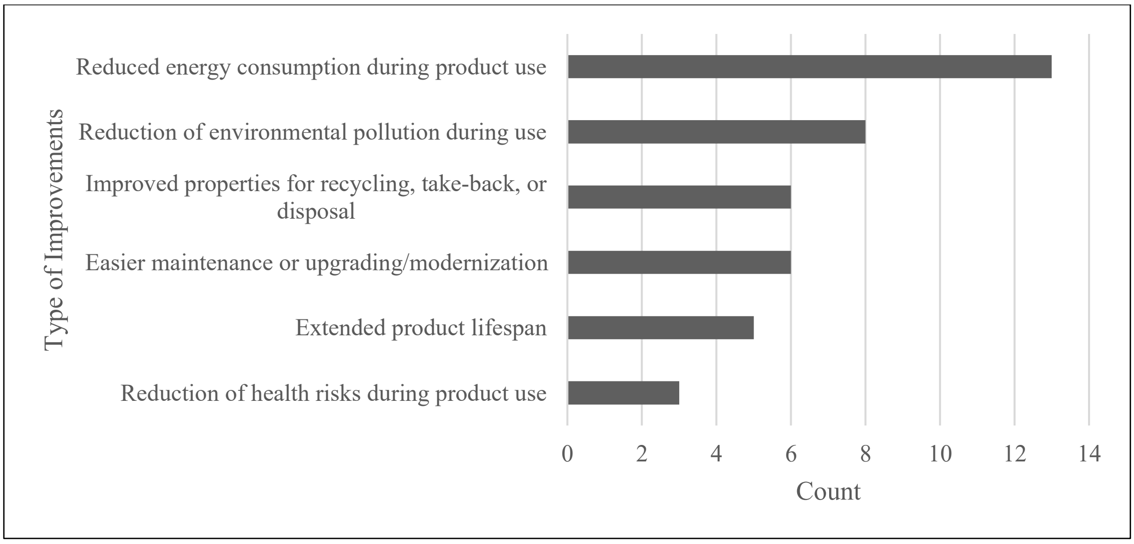

Figure 1 – Types of environmental improvements reported by companies

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4.2 Relationship Between Firm Size and Product Innovation

This subsection investigates the relationship between enterprise size and the likelihood of introducing innovations. A contingency table (Table 2) was constructed to compare firm size with the presence of product innovation reported by the firm.

Table 2 – Product innovation by firm size category

Firm Size	No Innovation	Innovation
Small enterprises	22	7
Medium-sized enterprises	31	21
Large enterprises	7	13

To assess the statistical significance of the observed association between firm size and product innovation, a chi-squared test of independence was applied. The results of the test are summarized in Table 3.

Table 3 – Chi-squared test results for the association between firm size and product innovation

Test Statistic	Value
Chi-squared statistic	8.20
Degrees of freedom	2
p-value	0.0166

The resulting p-value indicates a statistically significant association at the 5% significance level. This suggests that enterprise size and product innovation are not independent: medium-sized and large enterprises are significantly more likely to implement product innovations compared to their smaller counterparts.

4.3 Relationship Between Industry and Product Innovation

This subsection examines the relationship between the industrial sector and the likelihood of introducing product innovations among manufacturing enterprises. The analysis aims to statistically assess whether a significant association exists between industry type and product innovation, that is, whether the rate of innovation varies depending on a firm's affiliation with a particular industrial sector.

Table 4 illustrates the distribution of product innovation activity across various industrial sectors.

Table 4 – Product innovation by industry sector category

Industry	No Innovation	Innovation
Energy	1	0
Medical devices	1	0
Paper industry	1	0
Printing industry	1	0
Rubber industry	0	1
Services	1	0
Construction	2	1
Light industry	0	3
Pharmaceutical	2	1
Textile	2	1
Automotive	3	2
Metallurgical	2	4
Woodworking	6	1
Chemical	3	5
Electrical engineering	5	3
Food industry	11	8
Mechanical engineering	19	11

To assess whether there is a statistically significant association between industry sector and the introduction of product innovations, a chi-squared test of independence was applied. The results of the test are presented in Table 5.

Table 5 – Chi-squared test results for the association between industry and innovation activity

Test Statistic	Value
Chi-squared statistic	15.00
Degrees of freedom	16
p-value	0.5245

The resulting p-value of 0.5245 is well above the conventional 5% significance threshold, indicating that there is no statistically significant relationship between industry type and innovation activity in the analysed sample. In other words, the likelihood of introducing product innovations does not differ significantly across industrial sectors.

4.4 Relationship Between Firm Size and Product Eco-Innovation

This section explores whether there is a statistically significant relationship between enterprise size and the adoption of product eco-innovations in Slovak manufacturing companies, using cross-tabulation and a chi-squared test of independence based on survey data.

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The cross-tabulated data are presented in Table 6. Firms were classified by size according to the number of employees, using standard EU thresholds as detailed in Chapter 3. Eco-innovation activity was measured using the binary variable (1 = product eco-innovation introduced; 0 = product eco-innovation not introduced).

Table 6 – Product eco-innovation by firm size category

Firm Size	No Eco-Innovation	Eco-Innovation
Small enterprises	25	4
Medium-sized enterprises	43	9
Large enterprises	12	8

Table 7 – Chi-squared test results for the association between firm size and product eco-innovation

Test Statistic	Value
Chi-squared statistic	5.73
Degrees of freedom	2
p-value	0.0571

The results of the chi-squared test are presented in Table 7. Although the p-value of 0.0571 is slightly above the conventional 5% threshold, the result indicates a marginally significant association between enterprise size and product eco-innovation at the 10% level. The observed trend suggests that larger enterprises are more likely to implement product eco-innovations compared to smaller ones.

4.5 Relationship Between Industry and Product Eco-Innovation

21 companies (20.79% of the total sample; 51.22% of innovators) stated that their product innovations had a positive environmental impact, for example, through lower energy consumption, reduced material use, or improved recyclability. These cases can be classified as product eco-innovations, as they explicitly contribute to environmental performance improvements during the use or disposal phase of the product.

The sectoral distribution provides valuable insights into innovation patterns; therefore, this subsection examines how the implementation of product eco-innovation varies across different industrial sectors. The association between industrial sector and product eco-innovation was analysed using contingent tables and a chi-squared test of independence.

The cross-tabulated data are presented in Table 8. Firms were classified by sector (see Table 1) and product eco-innovation activity (using the binary variable: 1 = product eco-innovation introduced; 0 = product eco-innovation not introduced).

The statistical analysis using the chi-squared test (see Table 9) found no significant association between industry and the likelihood of implementing product eco-innovation ($\chi^2 = 13.37$, df = 16, p = 0.6455). This suggests that, despite observable differences in absolute numbers, the adoption of product eco-innovation is not strongly dependent on the industry sector.

Table 8 – Product eco-innovation by industry

Industry	No Eco-Innovation	Eco-Innovation
Mechanical engineering	26	4
Food industry	15	4
Chemical	5	3
Electrical engineering	5	3
Metallurgical	4	2
Automotive	3	2
Woodworking	6	1
Light industry	2	1
Rubber industry	0	1
Construction	3	0
Pharmaceutical	3	0
Textile	3	0
Energy	1	0
Medical devices	1	0
Paper industry	1	0
Printing industry	1	0
Services	1	0

Table 9 – Chi-squared test results for the association between industry and product eco-innovation

Test Statistic	Value
Chi-squared statistic	13.37
Degrees of freedom	16
p-value	0.6455

4.6 Relationship Between Firm Size and Specific Environmental Improvements of Products

This subsection examines the relationship between the size of manufacturing firms and the implementation of specific environmental improvements in products. Environmental innovations can take various forms, including reduced energy consumption during product use, decreased environmental pollution, easier maintenance or upgrading, improved recyclability, extended product lifespan, or reduced health risks for users. The objective of the analysis was to determine whether firm size (small, medium, or large) has a statistically significant influence on the likelihood of adopting these improvements.

To assess potential associations, the chi-square test of independence was applied to compare the distribution of environmental improvements across firm size categories. Additionally, Cramér's V was calculated to measure the strength of association between firm size and each type of improvement. The results of these tests are presented in Table 10, which includes the chi-square statistic (χ^2), p-values, values of Cramér's V, and statistical significance at the 0.05 level.

Table 10 – Association between firm size and specific environmental improvements of (new or improved) products

Output Variable	χ^2	p-value	Cramer´s V	Significant
Reduced energy consumption during product use	2.36	0.307	0.15	No
Reduction of environmental pollution during use	1.42	0.492	0.12	No
Easier maintenance or upgrading/modernization	8.90	0.012	0.30	Yes
Improved recycling, take-back, or disposal	1.35	0.509	0.12	No
Extended product lifespan	0.68	0.711	0.08	No
Reduction of health risks during product use	4.77	0.092	0.22	No (Yes*)

Remark: * at $\alpha = 0.1$

The findings show that out of the six examined product improvements, only one - "easier maintenance or upgrading/modernization" demonstrated a statistically significant relationship with firm size ($\chi^2 = 8.90$; $p = 0.012$). The corresponding Cramér's V value of 0.30 indicates a weak to moderate association. For the remaining improvements, no statistically significant association was found, as all p-values exceeded 0.05 and Cramér's V values ranged from 0.08 to 0.22, suggesting very weak to weak relationships. In the specific case of "Reduction of health risks", the relationship is significant at the 0.1 level.

4.7 Relationship Between Industry and Specific Environmental Improvements of Products

This subsection examines the relationship between the industry sector and the implementation of specific eco-innovations in products. Similar to the previous subsection, the results are summarised in Table 11, which displays the chi-square statistics, p-values, and effect sizes, expressed as Cramér's V, for each type of product eco-innovation.

Table 11 – Association between industry and specific environmental improvements of (new or improved) products

Output Variable	χ^2	p-value	Cramér's V	Significant
Reduced energy consumption during product use	7.34	<0.007	0.27	Yes

Reduction of environmental pollution during use	41.49	<0.001	0.64	Yes
Easier maintenance or upgrading/modernisation	11.38	0.001	0.34	Yes
Improved recycling, take-back, or disposal	15.3	<0.001	0.39	Yes
Extended product lifespan	28.08	<0.001	0.53	Yes
Reduction of health risks during product use	11.38	0.057	0.34	No (Yes*)

Remark: * at $\alpha = 0.1$

The results presented in Table 11 indicate that several specific environmental impacts resulting from eco-innovations are significantly associated with the type of industry. In particular, reduced energy consumption showed a statistically significant association ($\chi^2 = 7.34$; $p < 0.007$) with a small to moderate effect size (Cramér's V = 0.27). This suggests that while energy-saving measures are relatively common across manufacturing firms, their implementation differs by sector.

The strongest association was found for the reduction of environmental pollution ($\chi^2 = 41.49$; $p < 0.001$), with a large effect size (Cramér's V = 0.64). This indicates substantial disparities among industries in their ability or willingness to reduce emissions and environmental burdens. A significant relationship was also observed for easier maintenance or upgrading/modernization ($\chi^2 = 11.38$; $p = 0.001$), accompanied by a moderate effect size (Cramér's V = 0.34), recycling, take-back, or disposal ($\chi^2 = 15.30$; $p < 0.001$; Cramér's V = 0.39) and extended product lifespan ($\chi^2 = 28.08$; $p < 0.001$; Cramér's V = 0.53), suggesting that circular economy principles are adopted unevenly across industrial sectors.

In contrast, reduction of health risks during product use did not reach statistical significance at the 0.05 level ($\chi^2 = 11.38$; $p = 0.057$), but only at the 0.1 level. Together with a moderate effect size (Cramér's V = 0.34), this suggests that health-related considerations are also unevenly distributed across industrial sectors. Overall, the findings underscore significant sectoral variation in specific eco-innovations of products.

4.8 Spearman Correlation Analysis of Specific Types of Product Eco-Innovations

This section presents the results of a Spearman correlation analysis exploring the relationships between specific eco-innovations in new products reported by manufacturing firms. As shown in Table 12, the correlations between the examined types of product eco-innovations are mostly weak to moderate, suggesting that these improvements often occur independently. However, certain patterns indicate that some types of environmental improvements may co-occur or complement one another, while others may reflect differing or even conflicting innovation objectives.

Table 12 – Association between industry and specific environmental improvements of eco-innovations in manufacturing enterprises

	a	b	c	d	e	f
a	1					
b	0.35	1				
c	0.41	-0.19	1			
d	0.41	0.03	-0.05	1		
e	-0.04	0.48	-0.21	0.02	1	
f	-0.23	-0.19	-0.05	-0.31	-0.21	1

Note: a – Reduced energy consumption; b – Reduction of environmental pollution; c – Easier maintenance or upgrading/modernisation; d – Improved recycling, take-back, or disposal; e – Extended product lifespan; f – Reduction of health risks during product use

The highest positive correlations were found between the reduction of environmental pollution (b) and the extension of product lifespan (e) ($\rho = 0.48$). This indicates that reducing environmental burdens during use and prolonging the useful life of products may be interconnected goals in certain industries.

A moderately strong positive correlation was also found between reduced energy consumption (a) and both easier maintenance or upgrading (c) and improved recycling, take-back, or disposal (d), with correlation coefficients of $\rho = 0.41$ in both cases. This suggests that these types of product eco-innovations may complement each other.

On the other hand, several weak to moderate negative correlations were detected. For example, improved recycling, take-back, or disposal (d) showed a stronger negative relationship with health risk reduction (f) ($\rho = -0.31$), and reduced energy consumption (a) was negatively associated with reduced health risks during product use (f) ($\rho = -0.23$).

5 DISCUSSION AND CONCLUSION

Environmental innovations are becoming increasingly important due to different reasons, such as regulatory pressure, societal demand for sustainability, and strategic shifts toward greener production. Our study is therefore focused on product eco-innovation from a CE perspective, while it addresses sectoral variations and variations related to firm size.

The main findings are as follows. Contrary to much of the existing literature, the likelihood of adopting product innovations and eco-innovations does not significantly differ across industrial sectors – though we do observe notable sectoral variation in the types of eco-innovations implemented. Larger firms are generally more likely to introduce product innovations and eco-innovations, but firm size does not play a decisive role in the adoption of specific types of product eco-innovations. Most types of product eco-innovations occur independently, but certain ones, such as reduction of pollution and the extension of product lifespan, tend to complement each other, whereas others, like improved recyclability and health risk reduction, tend to have conflicting adoption patterns. The main findings are further discussed in detail.

5.1 Industry Sector and Product Eco-Innovation

Our results show that the likelihood of introducing product innovations does not differ significantly across industrial sectors. These findings suggest that industry classification is not a decisive factor in shaping innovation behaviour. It is in contrast with a vast literature that argues that different sectors follow distinct innovation trajectories - shaped by their dominant activities - which reflect variations in technology sources, user requirements, and opportunities for knowledge appropriation (Pavitt, 1984). Additionally, new empirical studies, such as Alos-Simo, Verdu-Jover and Gomez-Gras (2020), suggest that every industry is influenced by sector-specific technology, which affects innovation in goods and services; however, these technological differences remain unclear in the context of eco-innovation. Also, Bal-Domańska, Stańczyk and Szewczyk (2025) have argued, based on their research in Polish industry, that each sector has unique regulatory requirements, competitive dynamics, and resource availability (e.g. the chemical industry might be more sensitive to regulatory pressure related to emissions, while the food industry might focus on sustainability-based reputation building).

Despite the limited number of studies, those available show the existence of differences in the likelihood of product eco-innovations between manufacturing sectors. For example, Clausen's (2021) results reveal that the diffusion of environmental product and service innovations differs considerably between sectors, and Marin and Lotti's (2017) results show that the propensity to innovate varies substantially across sectors. In addition, Horbach (2008) showed differences between groups of sectors, while arguing that especially branches like (electrical) machinery or motor vehicles that have high export shares and that are highly exposed to international competition are more likely to innovate. Our study does not align with prior studies, as it reveals that there are no statistically significant differences in product eco-innovation adoption among firms across different sectors. However, despite the study of Biscione *et al.* (2022) finding that there is a sector-specific effect of eco-innovation, they also concluded that other internal drivers are essential to explain a firm´s decision to boost eco-innovation rather than industry-specific characteristics (Biscione *et al.*, 2022).

Interestingly, in contrast to our previous findings, our results in Section 4.7 show substantial sectoral variation in the types of eco-innovations associated with new products, underscoring the heterogeneity of adoption across manufacturing industries.

5.2 Firm Size and Product Eco-innovation

According to our study, firm size plays a key role: medium and large enterprises were significantly more likely to introduce any product innovations (χ^2 = 8.20, p = 0.0166) and showed a marginally significant tendency toward product eco-innovations (χ^2 = 5.73, p = 0.0571). This aligns with other studies from Central and Eastern Europe (CEE). Przychodzen and Przychodzen (2015) conclude that eco-innovators are larger, more likely to face lower financial risk exposure and possess greater free cash flows than other firms. This also corroborates with other prior studies highlighting the importance of financial and organisational resources in facilitating eco-innovation (Vicianová *et al.*, 2017; Vokoun and Jílková, 2020). In the European context, Rodríguez-Rebés *et al.* (2024) have confirmed that larger companies tend to innovate more than smaller ones, particularly in terms of eco-innovation. In contrast, our study found the most significant relationship to be in the case of innovation, and only marginally significant for eco-innovation. The importance of firm size in eco-innovations is supported by other studies, such as Maman, Dias and Bassi (2024), which show that the number of employees has an impact on environmentally friendly practices, and by Carfora *et al.* (2022), who identify firm size as one of the three basic determinants for adopting eco-innovations. It is worth noting that there are also studies (e.g., Horbach, 2008) that did not find a relationship between eco-innovation (specifically, product eco-innovation) and firm size. In the CE context, studies that specifically examine innovations towards the CE have also concluded that larger companies are more likely to adopt circular eco-innovations (Córcoles and Triguero, 2025), respectively, that SMEs' short-term vision limits their environmental management to legal requirements, systematisation and cost savings (Ormazabal *et al.*, 2018).

Interestingly, in contrast to the previous findings presented above, our results suggest that firm size generally does not play a decisive role in the adoption of specific types of product eco-innovations, with the exception of innovations related to product maintenance and upgrading.

6 CONCLUSIONS

This study contributes to the understanding of how Slovak manufacturing firms adopt product eco-innovations within the context of the circular economy. While the overall likelihood of product eco-innovation adoption does not significantly vary across industry sectors, notable sectoral differences exist in the specific types of eco-innovations implemented. Larger firms are more likely to introduce product eco-innovations, though the influence of firm size on specific eco-innovations is limited. The findings also reveal that certain types of eco-innovations, such as pollution reduction and product longevity, tend to co-occur, suggesting complementary innovation pathways. Overall, the research highlights the heterogeneous and selective nature of product eco-innovation adoption across manufacturing firms.

Theoretical Implications:

This research contributes to the theoretical discourse on product eco-innovation by emphasizing the importance of distinguishing between general adoption and adoption of specific types of eco-innovation. It challenges the common assumption that sectoral affiliation is a strong predictor of general product eco-innovation behaviour, suggesting instead that factors such as firm size may play a more significant role.

While this holds true for general adoption, the relationship is quite different when examining specific types of product eco-innovations. Drawing on the statement by Prieto-Sandoval, Jaca and Ormazabal (2018) that product eco-innovations are one of eight types of eco-innovations that support the CE, our study delves deeper by analysing specific types, including those directly related to CE.

The correlation analysis revealed moderate positive and negative correlations among certain types of product eco-innovations. However, it did not show a consistent pattern of joint adoption for CE-related innovations, such as reduced energy consumption, easier maintenance or upgrading, extended product lifespan, and easier recycling.

Furthermore, the results indicated significant sectoral differences in the adoption of these specific types of product eco-innovations, but no notable differences based on firm size. Therefore, we conclude that it is important to recognise the distinct sectoral patterns associated with the adoption of specific types of product eco-innovation. It is unrealistic to expect that firms will adopt all CE-related product eco-innovations within a short time frame.

Practical Implications:

For policymakers and practitioners, the findings underscore the need for targeted support strategies. While broad policy incentives might not yield sector-specific adoption, tailored interventions could stimulate particular types of product eco-innovations where they are underrepresented. For managers, the insights point to the possible trade-offs and synergies in the adoption of specific combinations of product eco-innovations.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.