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Barriers to green manufacturing implementation in industrial enterprises

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Abstract: The paper analyses barriers to the implementation of green manufacturing in industrial enterprises in Slovakia, focusing on financial, technological, and organizational barriers. Based on a questionnaire survey, the main obstacles were identified, including insufficient investment, a lack of skilled labour, and limited access to green resources. To evaluate regional and size-related differences, the Chi-square test was applied to determine whether the occurrence of barriers varies according to the geographical location or size of the enterprise. The results of the analysis did not show statistically significant differences between regions in Slovakia or between enterprise size categories, indicating that the barriers to implementing green manufacturing have a nationwide character. However, the most frequent barriers were found to be insufficient financial resources, a shortage of qualified employees, and limited availability of raw materials and technological infrastructure. These factors negatively affect the eco-innovation performance of enterprises, reducing their ability to implement green manufacturing principles and respond effectively to identified barriers. A comparison with the Eco-Innovation Index 2024 further confirmed Slovakia's below-average performance within the European Union, highlighting insufficient investment in eco-innovation, weak cooperation between the public and private sectors, and limited government support. The findings suggest that overcoming these obstacles requires the development of targeted financial mechanisms, stronger institutional support, and the integration of environmental training programs for employees. This paper aims to identify the main barriers to the implementation of green manufacturing in industrial enterprises in Slovakia and to analyse their differences between regions and individual enterprise size categories.

1 Introduction

Green manufacturing is an approach that focuses on minimizing the negative environmental impacts of manufacturing, optimizing material flows, and maintaining or improving economic efficiency. This concept includes technologies and practices such as waste reduction, energy savings, and the use of renewable resources [1]. In recent years, there has been growing pressure on industrial enterprises to implement more environmentally friendly solutions, driven by increasing environmental regulations, social requirements, and need for sustainability [2].

Despite the clear advantages of green strategies, many enterprises encounter financial, technological, and organizational barriers that hinder their implementation in manufacturing processes. Several studies confirm that the most significant barriers include a lack of investment, skilled workers, insufficient management support, and ineffective supplier relationships [1,3], which lead to limited availability of green materials and technologies [4].

These factors have a fundamental impact on enterprises' decisions to switch to green manufacturing and can significantly slow down the ecological transformation of industry.

The most common barriers to the implementation of green manufacturing and its approaches are:

1. Lack of initial investment

One of the most frequently identified barriers to implementation of green manufacturing is a lack of initial investment resources. Enterprises, especially small and medium-sized ones, often struggle with uncertainty about the return on investment of green projects [5], which discourages them from introducing green technologies. Investments in green solutions such as green hydrogen, green IT systems, and green supply chains are capital-intensive [6]. Financial barriers are further compounded by the unavailability of public or private investment inducements [7,8].

2. Lack of qualified employees

The green transition requires new skills, particularly in the areas of digital technologies, environmental management, and the circular economy, as well as expertise in the technical aspects of logistics and information flow management. However, many enterprises face a shortage of workers with the relevant skills [9,10]. In addition, there is a lack of systematic training programs and incentives to build a green culture within work teams [8,11]. The introduction of a cross-disciplinary approach that also integrates green manufacturing within Industry 4.0 and 5.0 requires trained personnel capable of adapting to process changes [12].

3. Insufficient support from top management

Lack of interest or weak awareness among top management about the importance of green manufacturing is one of the key obstacles to progress [13]. The transition to sustainable manufacturing systems requires not only a decision by enterprise management but also active support in the form of a vision, internal policies, and investment in human capital flow [14]. Especially in small enterprises, the environmental agenda is often subordinated to short-term goals [15].

4. Nonoptimal supplier relationships

Cooperation in supply chains and effective supply chain management are important for the environmental optimization of the entire manufacturing cycle. However, if suppliers are not involved in the green strategy, inconsistencies and risks are raised [14]. Problems also stem from a lack of trust, poor communication, and a lack of technical know-how among partners [16,17].

5. Lack and availability of resources

The introduction of green manufacturing requires access to suitable raw materials, renewable energy sources, physical infrastructure, and data. A lack of these capacities often obstructs progress [18]. In addition to physical resources, the availability of high-quality environmental data is also important, but this is limited in many enterprises [8,19].

6. Resistance to implementing new technologies

Innovations such as green manufacturing cells, digital twins, and intelligent energy optimization are among the key elements of effective sustainability, but their implementation is often slowed by a lack of trust and the risk of disrupting stable manufacturing [20]. Enterprises fear technological incompatibility between existing and new systems, as well as a loss of competitiveness in the event of failure [8].

7. Deficiencies in organizational structure

Organizational barriers, such as excessive hierarchy, slow decision-making, or unclear responsibilities, significantly affect the effectiveness of environmental measures [2,21]. The transformation towards green manufacturing requires more flexible structures with a focus on teamwork, accountability, process agility, and the interconnection of manufacturing, distribution, and information flows [22].

8. Insufficient government support

Public policies have a fundamental impact on the pace of transformation of manufacturing enterprises. Insufficient legislative certainty, weak regulatory measures, a lack of stimulus, and low environmental awareness slow down green transformations [8]. Enterprises expect clear guidance from the state, not only in the form of standards, but also in the areas of infrastructure, research, and financing that support green manufacturing and green logistics, as well as ecologically optimized material and information flows [6,7].

Several studies confirm that the region in which an enterprise operates, and the size of the enterprise are among the key factors influencing the ability of enterprises to implement green innovations and sustainable manufacturing approaches. Large enterprises often have better access to technology, finance, and innovation, which enables them to implement environmental measures more effectively. Conversely, smaller enterprises face greater financial and personnel limitations, which can hamper their ability to implement green strategies [23,24].

Geographical factors, such as location within a country or region, influence the availability of infrastructure, the regulatory environment, and market conditions. Enterprises in economically stronger regions or areas with more developed infrastructure are better placed to implement green innovations due to their greater access to finance and innovation [23,25]. At the same time, it appears that the effectiveness of environmental policies and their impact on enterprises varies according to local socio-technical systems and regional characteristics [23,26].

This paper aims to identify the main barriers to the implementation of green manufacturing in industrial enterprises in Slovakia and to analyse their differences between regions and individual enterprise size categories.

The paper also compares the situation in Slovakia with other European Union countries based on the Eco-Innovation Index 2024, providing a broader view of the issue and allowing for the identification of common and specific challenges in different economic contexts.

2 Methodology

The first step of the research was to process the theoretical foundations of the issue based on scientific contributions selected according to their relevance and year of publication. Preference was given to contributions published in the last decade that focused on the issue of barriers to green manufacturing in industrial enterprises. The overview of the professional literature thus obtained provided a basis for formulating research questions, hypotheses, a questionnaire, data collection, and subsequent analysis of the results.

Research questions (RQ):

RQ1: What barriers to the implementation of green manufacturing are most identified by industrial enterprises in Slovakia?

RQ2: What barriers to the implementation of green manufacturing are most identified in small and medium-sized enterprises and which in large enterprises in Slovakia?

Research hypotheses (RH):

RH1 (regions): There are differences between Slovak regions in terms of the identified barriers to the implementation of green manufacturing in industrial enterprises.

RH2 (enterprise size): There are differences between enterprises of different sizes in the barriers identified to the implementation of green manufacturing in industrial enterprises.

The research was conducted through a questionnaire survey in industrial enterprises in Slovakia, with respondents answering questions about the geographical location of the enterprise, its size category, and the identification of the main barriers to the implementation of green manufacturing principles.

The research was conducted using an online questionnaire, and the collected data were processed in MS Excel and analysed using Spyder 5.5.1 software. The research for this paper aimed to determine the current state of identified barriers to the implementation of green manufacturing, whether there is a statistically significant difference in the presence of barriers between regions of Slovakia, and whether there is a difference in the identified barriers to green manufacturing between enterprises according to size classification. To verify regional differences and differences between size categories of industrial enterprises, a chi-square analysis was used to test statistically significant differences in the presence of barriers between regions of Slovakia and between size categories of industrial enterprises. The results of the research are presented graphically and in tables.

An anonymous questionnaire was distributed to industrial enterprises in the Slovak Republic. The respondents to the questionnaire survey were selected enterprises from the “C industrial manufacturing“ group that conduct enterprise activities in Slovakia, and their number as of December 31, 2023, was 30,020 in total. According to the SK NACE classification under the following numerical codes and names (SK NACE is an abbreviation for the Statistical Classification of Economic Activities in the Slovak Republic, which is the national version of the European NACE Rev. 2 classification), categories 23, 24, 25, 26, 27, 28, 29, 30, and 32 were included in the analysis. Different enterprises may have multiple SK NACE classifications depending on their activities. We sent the questionnaire to energy and material-intensive industrial enterprises that have a significant environmental impact and are subject to strict environmental regulations. Given the high levels of emissions, waste, and raw material consumption, green manufacturing is essential to ensure sustainability in these sectors. The questionnaire wasn't distributed to other sectors because non-manufacturing sectors and light industry do not have as significant an environmental impact as the selected industrial categories. We sent the questionnaire to 750 industrial enterprises, representing 2.5% of the total sample of 30,020 industrial enterprises. The survey lasted two months. By the last day of data collection (February 29, 2024), a total of 88 respondents had completed the questionnaire, meaning that the response rate was 11.4%. We approached employees from the following areas of activity: environmental department, occupational health and safety department, quality and sustainability department, development and innovation department, purchasing and logistics department, manufacturing and technical department, and senior management. The sample of responding enterprises was divided according to EU Recommendation 2003/361/EC based on the number of employees. The resulting values for each size category are shown in Table 1.

Table 1 Distribution of enterprises by number of employees in absolute and relative terms

	Absolute frequency	Relative frequency
Micro enterprises / up to 10 employees	10	11.36%
Small enterprises / up to 50 employees	23	26.14%
Medium enterprises / up to 250 employees	37	42.05%
Large enterprises / more than 250 employees	18	20.45%

The largest representation in the survey is the group of medium-sized enterprises, followed by the group of small enterprises. The enterprises were also divided according to their geographical location into individual regions of the Slovak Republic, as shown in Figure 1. The largest representation of manufacturing enterprises is from the Trenčín, Bratislava, and Trnava regions.

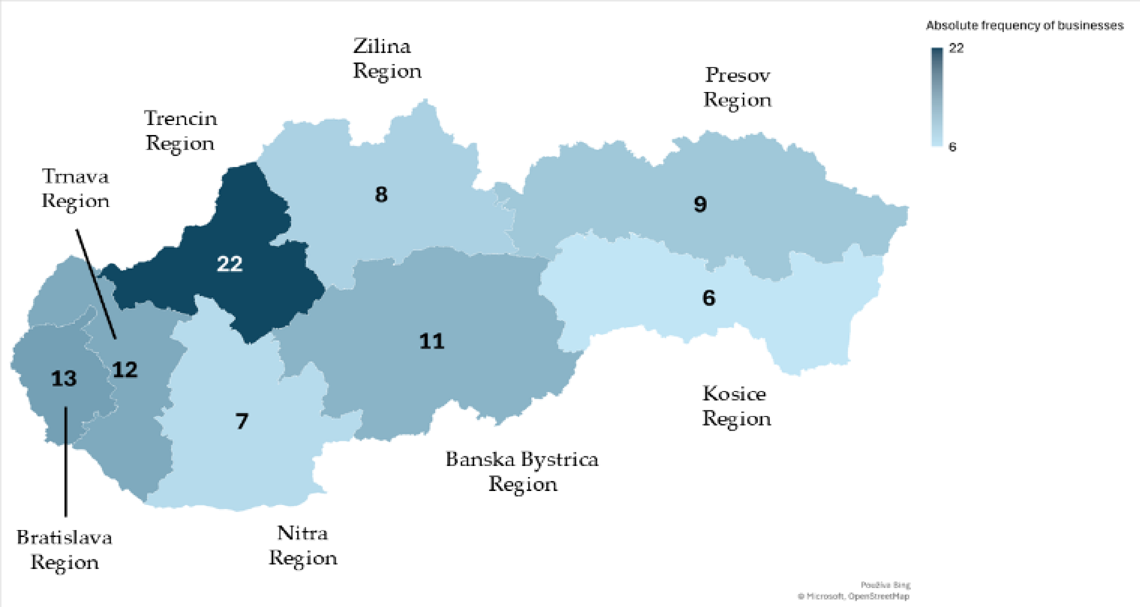

Figure 1 Representation of enterprises from individual regions in absolute numbers

Geographical factors can influence the intensity of barriers to green manufacturing implementation in Slovakia's industrial enterprises. Enterprises in economically stronger regions, such as the Bratislava region, may have better access to financing and skilled labour, which allows them to overcome obstacles for easier implementation of green solutions. Conversely, in regions with lower economic performance, such as the Prešov and Banská Bystrica regions, the dominant barriers may be a lack of investment, limited technological infrastructure, and a shortage of skilled workers.

To verify regional differences in the presence of financial, technological, organizational, and legislative barriers, a chi-square analysis was applied to test statistically significant differences in their frequency between regions.

To verify both hypotheses, individual barriers (lack of initial investment, lack of skilled workers, unavailability of resources, resistance to new technologies, shortcomings in organizational structure, insufficient support from management, suboptimal relationships with suppliers, and insufficient state support) were tested separately and collectively using the chi-square test.

The chi-square test compares the observed and expected frequencies of barriers in individual regions and determines whether the differences between them are random or statistically significant.

The P-value is used to decide on the statistical significance of differences at a chosen significance level of $\alpha = 0.05$.

The results of this analysis provide an overview of regional differences and differences in enterprise size in terms of barriers to green manufacturing and enable the identification of specific factors influencing the implementation of green solutions in individual regions of Slovakia and in enterprises according to size.

The analysis also focused on comparing the situation in Slovakia in terms of introducing eco-innovations into the economy, manufacturing, and consumption with other European Union countries based on the Eco-Innovation Index 2024, thus providing a broader view of the issue and enabling the identification of common and specific challenges in different economic contexts. The results of the research, which analyse regional and size differences between enterprises in identifying these barriers, provide an overview of the barriers to the implementation of green manufacturing in industrial enterprises in Slovakia.

3 Results and discussion

One of the results of the analysis conducted through a questionnaire survey in Slovakia is that the selected barriers generally present in several economies around the world, which we describe in the "Introduction" section, are also faced by enterprises in Slovakia.

Result 1 - RQ1: What barriers to the implementation of green manufacturing are most identified ***by industrial enterprises in Slovakia?***

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Figure 2 shows the absolute frequency of individual barriers encountered by industrial enterprises in Slovakia in their practice. Respondents could select multiple options for each question.

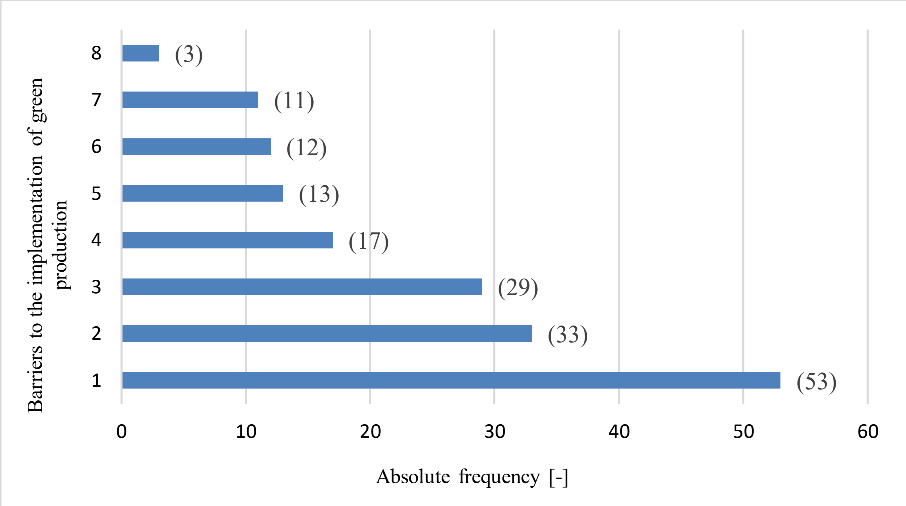

Figure 2 Absolute frequency of responses regarding existing barriers

Legend: (The same legend applies to Table 2 and Table 4)
1. Lack of initial investment (most significant barrier)
2. Lack of qualified employees
3. Lack and availability of resources
4. Resistance to implementing new technologies
5. Deficiencies in organizational structure
6. Insufficient support from top management
7. Suboptimal supplier relationships
8. Insufficient government support (least significant barrier)

The most significant obstacle is the lack of initial investment, which was identified as the main problem by 53 of the 88 respondents (60.2%). The lack of qualified employees is the second most frequently cited barrier, with 33 industrial enterprises (37.5%) involved in the survey facing a shortage of green technology experts. The lack of resources and their availability make it difficult for 29 industrial enterprises (33%) to obtain environmentally friendly materials, which is also reflected in the disruption of supply and demand flows and the availability of suitable means of transport necessary to ensure continuity of manufacturing. The rejection of new technologies is a problem for 17 industrial enterprises involved in the survey, which points to a low willingness to invest in innovation due to high costs and uncertainty of return. Organizational barriers and weak support from top management reflect a lack of strategy in the area of green measures. Inefficient supplier relationships signal problems in securing green components, which affects manufacturing efficiency. The least significant obstacle insufficient government support indicates that enterprises perceive internal factors as a greater barrier than insufficient government support.

Result 2 – RQ2: What barriers to the implementation of green manufacturing are most identified in small and medium-sized enterprises and which in large enterprises in Slovakia?

We analysed the presence of barriers encountered by industrial enterprises in Slovakia, focusing on the size classification of enterprises and examining barriers in individual categories of industrial enterprises according to size. A specific comparison is shown in Figure 3.

Key findings:

• The most significant barrier in all categories is the lack of initial investment, which affects micro enterprises the most. Its impact decreases slightly as the size of the enterprise increases, but it remains a dominant factor even in medium-sized and large enterprises.

• The lack of skilled employees and limited availability of raw materials are key barriers in medium and large enterprises. This trend suggests that as the scale of manufacturing increases, so do the demands for skilled labour and material supplies flow.

• The rejection of new technologies and organizational limitations are present to a similar extent across all size categories, suggesting that these are systemic barriers not directly related to the size of the enterprise.

• Insufficient support from top management and ineffective supplier relationships are a problem across all categories, with the most significant impact on medium-sized enterprises. This may be related to their transition between small and large enterprises, where they face higher demands for supply chain management and coordination.

• Insufficient support from the state is the least significant barrier in all categories, suggesting that enterprises perceive other factors - particularly financing and human resources - as more important for implementing green manufacturing.

• Small, medium-sized, and large enterprises most frequently encountered the same barriers: lack of initial investment, lack of skilled employees, and limited availability of raw materials.

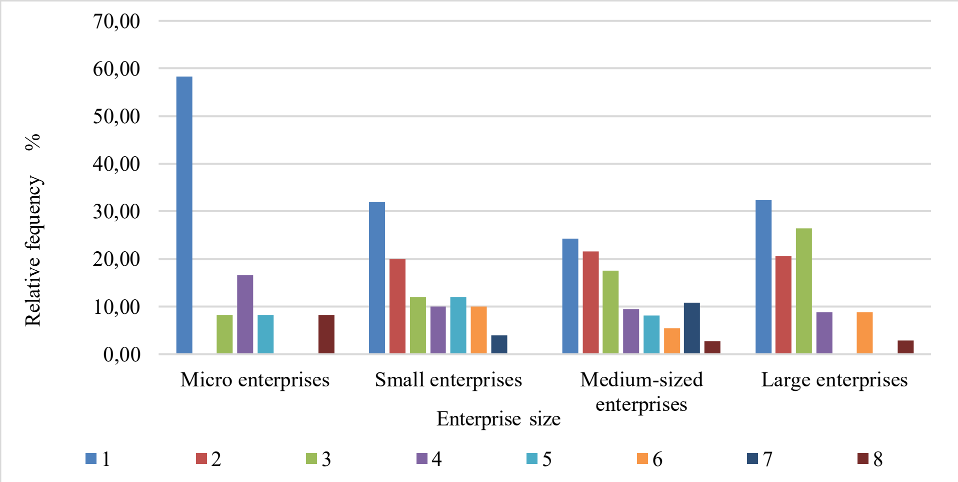

Figure 3 Barriers to the implementation of green manufacturing in industrial enterprises by size category in Slovakia

Legend:
1. Lack of initial investment (most significant barrier)
2. Lack of qualified workers
3. Lack and availability of resources
4. Resistance to implementing new technologies
5. Deficiencies in organizational structure
6. Insufficient support from top management
7. Suboptimal supplier relationships
8. Insufficient government support (least significant barrier)

Result 3 - RH1 (regions): There are differences between Slovak regions in the identified barriers to the implementation of green manufacturing in industrial enterprises.

The frequency of responses is shown in Table 2. For the purposes of evaluating research hypothesis 1, responses from the research questionnaire were compared.

Table 2 Barriers to the implementation of green manufacturing in individual regions

Barriers to the implementation of green manufacturing /Region	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
Trencin Region	13 (59.1%)	4 (18.2%)	7 (31.8%)	3 (13.6%)	3 (13.6%)	4 (18.2%)	0 (0.0%)	0 (0.0%)	22 (100%)
Bratislava Region	7 (53.8%)	5 (38.5%)	4 (30.8%)	2 (15.4%)	2 (15.4%)	1 (7.7%)	5 (38.5%)	0 (0.0%)	13 (100%)
Trnava Region	8 (66.7%)	6 (50.0%)	5 (41.7%)	4 (33.3%)	2 (16.7%)	2 (16.7%)	2 (16.7%)	2 (16.7%)	12 (100%)
Banska Bystrica Region	4 (36.4%)	5 (45.5%)	6 (54.5%)	3 (27.3%)	3 (27.3%)	0 (0.0%)	1 (9.1%)	0 (0.0%)	11 (100%)
Presov Region	4 (44.4%)	5 (55.6%)	1 (11.1%)	3 (33.3%)	2 (22.2%)	1 (11.1%)	0 (0.0%)	1 (11.1%)	9 (100%)
Zilina Region	8 (100.0%)	3 (37.5%)	2 (25.0%)	1 (12.5%)	0 (0.0%)	2 (25.0%)	2 (25.0%)	0 (0.0%)	8 (100%)
Nitra Region	4 (57.1%)	2 (28.6%)	2 (28.6%)	1 (14.3%)	1 (14.3%)	1 (14.3%)	1 (14.3%)	0 (0.0%)	7 (100%)
Kosice Region	5 (83.3%)	3 (50.0%)	2 (33.3%)	0 (0.0%)	0 (0.0%)	1 (16.7%)	0 (0.0%)	0 (0.0%)	6 (100%)
∑Sum	53 (60.2%)	33 (37.5%)	29 (33.0%)	17 (19.3%)	13 (14.8%)	12 (13.6%)	11 (12.5%)	3 (3.4%)	88 (100%)

To verify whether there are regional differences in the identification of barriers to the implementation of green manufacturing, a chi-square test of independence was used. The hypothesis tested was that the occurrence of individual barriers is evenly distributed among the regions of Slovakia and is not influenced by the geographical environment. Table 3 presents the results of separate tests for each barrier, showing the chi-square test statistics, degrees of freedom, and corresponding p-values.

Table 3 Results of the chi-square test for the relationship: region/ barriers to the implementation of green manufacturing

Pearson's Chi-Square Tests			
Barrier	**χ^2**	**df**	**p-hodnota**
1. Lack of initial investment	6.423	7	0.491
2. Lack of qualified employees	2.815	7	0.902
3. Lack and availability of resources	7.485	7	0.380
4. Resistance to implementing new technologies	3.545	7	0.831
5. Deficiencies in organizational structure	3.982	7	0.782
6. Insufficient support from top management	4.062	7	0.773
7. Suboptimal supplier relationships	**14.455**	**7**	**0.044**
8. Insufficient government support	5.360	7	0.616
Overall (all barriers combined)	38.546	49	0.846

Overall testing did not reveal any statistically significant differences between enterprises in different regions in terms of their perception of barriers ($\chi^2 = 38.55$; df = 49; p = 0.846). This means that an enterprise's regional affiliation does not significantly influence the overall pattern of identified barriers to the implementation of green manufacturing.
Subsequently, differences between regions were examined for each barrier separately. The results of chi-square tests showed that in most cases the differences between regions of Slovakia are not statistically significant. P-values were higher than 0.05 in all cases, except for one barrier. A statistically significant difference was confirmed for the barrier suboptimal relationships with suppliers ($\chi^2 = 14.455$; df = 7; p = 0.044). This means that enterprises in different regions of Slovakia perceive this barrier to the implementation of green manufacturing differently, which may indicate differences in the structure of supply chains and regional enterprises conditions. Other barriers achieved p-values significantly higher than 0.05, indicating that their perception is relatively consistent across regions. A more detailed analysis showed that the Bratislava region reported more significant problems with supplier relationships. In contrast, this barrier was not reported at all in the Trencin, Presov, and Košice regions. These results suggest that regional specifics of the enterprise environment may in some cases influence the intensity of individual barriers, especially those related to the supply chain.

Despite these differences, global testing of the overall dependence between regions and all barriers did not reveal a statistically significant association. This means that the regional environment as a whole is not a key factor in identifying barriers to green manufacturing in Slovakia.

Result 4 - RH2 (enterprise size): There are differences between enterprises of different sizes in the identified barriers to the implementation of green manufacturing in industrial enterprises.

We analysed the presence of barriers encountered by industrial enterprises in Slovakia, focusing on the size classification of enterprises and examining whether there is a difference in the presence of barriers between different size categories of enterprises. The frequency of responses is shown in Table 4. For the purposes of evaluating research hypothesis 2, responses from the research questionnaire were compared.

Table 4 Barriers to the implementation of green manufacturing in individual categories of enterprises

Barriers to the implementation of green manufacturing / Categories of enterprises	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
Large Enterprises	11 (61.1%)	7 (38.9%)	9 (50.0%)	3 (16.7%)	0 (0.0%)	3 (16.7%)	0 (0.0%)	1 (5.6%)	18 (100%)
Medium Enterprises	18 (48.6%)	16 (43.2%)	13 (35.1%)	7 (18.9%)	6 (16.2%)	4 (10.8%)	8 (21.6%)	2 (5.4%)	37 (100%)
Small Enterprises	16 (69.6%)	10 (43.5%)	6 (26.1%)	5 (21.7%)	6 (26.1%)	5 (21.7%)	2 (8.7%)	0 (6.5%)	23 (100%)
Micro Enterprises	8 (80.0%)	0 (0.0%)	1 (10.0%)	2 (20.0%)	1 (10.0%)	0 (0.0%)	1 (10.0%)	0 (0.0%)	10 (100%)
∑Sum	53 (60.2%)	33 (37.5%)	29 (33.0%)	17 (19.3%)	13 (14.8%)	12 (13.6%)	11 (12.5%)	3 (3.4%)	88 (100%)

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The chi-square test of independence was applied to identify possible differences between barriers to the implementation of green manufacturing depending on the size of the enterprises. Hypothesis 2 was tested. The table (Table 5) shows the results of separate tests for each barrier, namely the value of the test statistics, the number of degrees of freedom, and the corresponding p-value.

Table 5 Results of the chi-square test for the relationship: enterprise size/barriers to implementation of green manufacturing

Pearson's Chi-Square Tests			
Barrier	χ^2	**df**	**p-hodnota**
1. Lack of initial investment	4.790	3	0.188
2. Lack of qualified workers	3.102	3	0.376
3. Lack and availability of resources	2.911	3	0.406
4. Resistance to implementing new technologies	1.634	3	0.652
5. Deficiencies in organizational structure	2.447	3	0.485
6. Insufficient support from top management	1.558	3	0.669
7. Suboptimal supplier relationships	5.220	3	0.156
8. Insufficient government support	1.231	3	0.746
Overall (all barriers combined)	22.050	21	0.399

Overall testing did not reveal any statistically significant differences between enterprises of different sizes in their perception of barriers ($\chi^2 = 22.050$; df = 21; p = 0.399). This means that the size category of an enterprise is not a decisive factor in identifying barriers to the implementation of green manufacturing. Subsequently, the differences between enterprises for each barrier were analysed separately. The results showed that none of the barriers were statistically significantly different between enterprise size categories (all p-values > 0.05). The barriers that came closest to significance were Suboptimal relationships with suppliers ($\chi^2 = 5.220$; p = 0.156) and Lack of initial investment ($\chi^2 = 4.790$; p = 0.188). A more detailed analysis showed that micro-enterprises reported more frequent problems with investment and state support. Medium-sized enterprises more often emphasized barriers related to skilled labor and relationships with suppliers. Large enterprises encountered fewer organizational shortcomings and supplier relationship issues. However, these differences cannot be considered statistically significant. Overall, the results suggest that the barriers to green manufacturing are relatively similar across all enterprise size groups.

Result 5: Comparison of Slovakia within the Eco-Innovation Scoreboard (Eco-IS) in the EU

To better understand the context of green manufacturing implementation in Slovakia, it is useful to compare the country's performance in eco-innovation with other EU Member States. This is done using the Eco-Innovation Scoreboard (Eco-IS), which assesses EU countries based on 16 indicators divided into five areas [27]:

- **Inputs into eco-innovation –** investments in environmental research, human and financial resources;
- **Eco-innovation activities –** the extent to which enterprises are active in the field of environmental innovation;
- **Eco-innovation outputs –** number of patents, innovative solutions, and technological applications;
- **Resource efficiency –** resource productivity, energy consumption, CO_2 emissions;
- **Socio-economic results –** impact of eco-innovation on employment and economic growth.

According to the latest data for 2024, Slovakia achieved a score of 98.9 in the Eco-Innovation Index, which is below the EU average (100). This ranks Slovakia among countries with lower levels of eco-innovation performance. By comparison, countries such as Finland, Denmark, and Austria scored above 140, placing them among the leaders in eco-innovation. Slovakia still lags significantly behind Germany and Sweden, where investment in research and innovation in green manufacturing is high [28].

Key factors influencing Slovakia's low score:

- **Insufficient investment in eco-innovation –** Slovakia is among the countries with low levels of public and private investment in environmental solutions [29].
- **Weak cooperation between the public and private sectors –** low levels of research in the field of eco-innovation and insufficient links between academia and industry slowdown the transfer of innovation into practice [29].
- **Limited support from the state –** Slovakia has less effective regulatory mechanisms and support policies in the field of eco-innovation compared to other EU countries [30].

Figure 3 shows the Eco-Innovation Index for 2024, where Slovakia's position in comparison with other EU countries is visible.

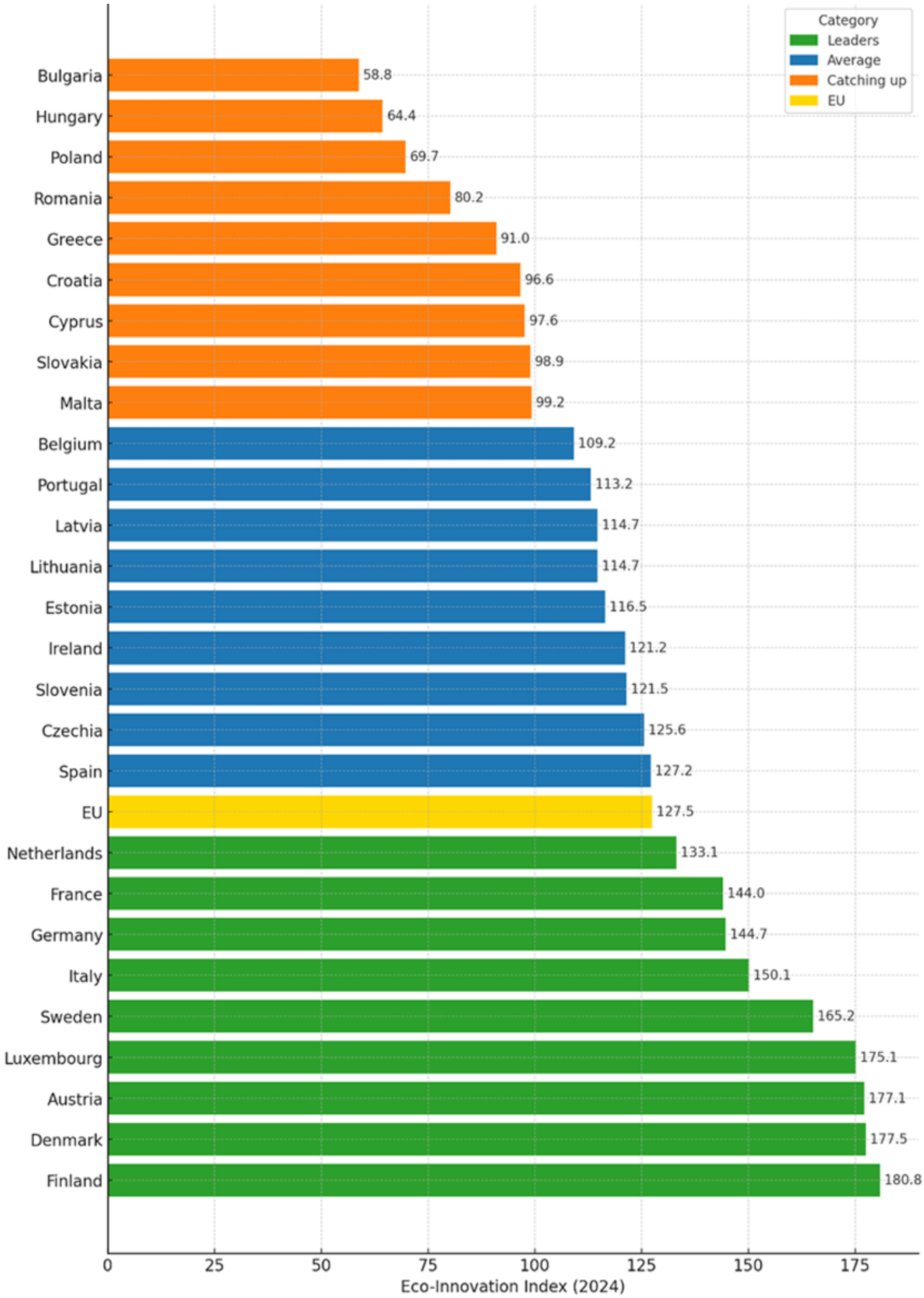

Figure 3 Eco-Innovation Index 2024: Country comparison EÚ [30]

This analysis provides a broader view of the problem of implementing green manufacturing in Slovak industrial enterprises and suggests that overcoming the identified barriers requires increased investment in eco-innovation, technological progress, and stronger support for research and development in environmental areas.

4 Conclusions

Research conducted in industrial enterprises in Slovakia identified the main obstacles to the implementation of green manufacturing, which include a lack of finance, a shortage of skilled workers, and ineffective supply chains. Regional analysis did not reveal any statistically significant differences between the regions of Slovakia. This finding contrasts with some studies that have reported different approaches to the implementation of green or sustainable manufacturing and specific barriers conditioned by the regional and infrastructural environment. Regional differences in the application of eco-innovations can be significant. For example, a study on regional technological capacities in Europe points out that areas with a historically strong technology sector have a higher rate of green transformation, with Germany among the leaders in this area [31]. Similar findings were reported in a study on regional differences in technological diversification in green transformation, which points to that economically strong regions are better positioned for green diversification, while weaker regions have significantly limited opportunities for transformation [32]. The absence of statistically significant regional differences in our research may be because Slovakia has less economic diversity in industry than, for example, Germany. By comparing our results with the work of Grillitsch & Hansen [33], it is possible to identify different approaches to the issue of green manufacturing and regional inequalities. The authors emphasize that the development of green industries depends on the type of region, with metropolitan regions having greater capacity for innovation and implementation of green technologies [33]. Differences compared to studies in other countries or parts of the world may be due to the small size of the country, lower economic diversity, and relatively low questionnaire response rates.

In the case of Slovakia, it appears that problems such as insufficient funding, weak links between research and practice, and the unavailability of qualified personnel are nationwide in nature. In terms of enterprise size, no statistically significant differences in barriers were confirmed. Based on the number of responses, small and medium-sized enterprises are most influenced by financial constraints, while large enterprises are more likely to encounter a shortage of skilled staff and technological support. These findings correspond with the findings of foreign studies. For example, Rizos et al. [34] and Alayón et al. [35] confirm that small enterprises in Europe often face limitations in accessing financing and information on environmental technologies, which also corresponds to the situation in Slovakia. Similar results were identified in [9] and [15], which showed that the size of an enterprise determines its ability to integrate the principles of sustainable development into its enterprise activities. According to these studies, the most significant barriers to the introduction of sustainability in small and medium-sized enterprises are financial, human, and institutional barriers. This study provides a systematic overview of the barriers to green manufacturing in Slovak industry based on statistical analysis, thereby complementing existing knowledge. The differences identified between the size categories of enterprises show that policies and support mechanisms need to be adapted to the specific needs of enterprises. For small and medium-sized enterprises, improving access to finance is key, while large enterprises need more effective training programs and technological support.

A limitation of this study is the relatively small sample size (88 enterprises), which may affect the representativeness of the results. Future research should focus on sectoral differences, long term trends, and the effectiveness of national policies in ecological transformation. Expanding the sample and taking regulatory and technological changes into account could contribute to a more accurate understanding of the obstacles and solutions in the field of green manufacturing. Nevertheless, it provides valuable insight into the issue of implementing green manufacturing approaches and environmental measures in industrial enterprises in Slovakia and allows the main barriers faced by enterprises to be identified. Although the research sample consisted of only 88 respondents, it can be concluded that even such data provide relevant insights into trends and challenges related to green manufacturing and barriers to its implementation.

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