Zhidebekkyzy, A., Temerbulatova, Zh., Kotaskova, A., & Németh, P. (2024). Catalysing responsible production: Evaluating the impact of EPR system on manufacturing enterprises. *Journal of International Studies, 17*(2), 178-190. doi:10.14254/2071-8330.2024/17-2/9

Journal of International Studies

Centre of Sociological Research

Scientific Papers

Catalysing responsible production: Evaluating the impact of EPR system on manufacturing enterprises

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Abstract. Responsible production has become increasingly vital in the global sustainability discourse, particularly in manufacturing. The extended producer responsibility (EPR) system is a critical policy mechanism that encourages manufacturers to reduce their environmental impact. Despite its growing significance, comprehensive studies assessing its effectiveness are sparse. Our research aims to address this gap by evaluating the influence of the EPR system on responsible production practices in European manufacturing enterprises. We employed the difference-in-differences (DiD) method to assess the impact, analysing panel data from 27 manufacturing enterprises across the Czech Republic, Poland, Slovakia, Romania, Estonia, Hungary, and Bulgaria, from 2010 to 2022. This method was chosen to mitigate endogeneity concerns. The results

Received: July, 2023
1st Revision: April, 2024
Accepted: May, 2024

DOI: 10.14254/2071-8330.2024/17-2/9

from the DiD analysis reveal a statistically significant positive impact of the EPR system on the circular material use rate, with an average increase of 10,5%. These findings indicate that the EPR system effectively enhances circular material use within the electronics manufacturing industry, a critical sector for advancing environmental sustainability.

Keywords: extended producer responsibility, responsible production, circular economy, sustainable manufacturing, difference-in-differences method, European manufacturing enterprises.

JEL Classification: Q53, Q56, L52, D22

1. INTRODUCTION

Responsible production and consumption are the main factors influencing the formation of an ecological economy. According to Sustainable Development Goal 12 proposed by the UN, responsible production aims to achieve economic growth while reducing environmental harm and developing safe and effective products for society (Dat & Hung, 2023; Handayani et al., 2024). In the long term, responsible production provides many advantages by saving resources, reducing costs, improving product quality, meeting modern requirements of society and consumers, and increasing social responsibility.

Extended Producer Responsibility (EPR) is a policy that holds producers responsible for the environmental costs of their products and is a crucial driver of responsible production. It encourages eco-design and waste minimisation (Gottberg et al., 2006) and has significantly motivated producers to develop eco-innovation (Peng et al., 2020).

The existing literature on EPR in manufacturing enterprises has primarily focused on the relationship between EPR, environmental regulations, and corporate performance (Peng, 2018), the role of customer integration in EPR practices, and its impact on market and financial performance (Lai et al., 2014; Mishchuk et al., 2023), the influence of organisational dimensions on EPR management and WEEE collection from households (Corsini et al., 2017). However, there is a research gap in assessing the overall effectiveness of the EPR system in manufacturing enterprises, particularly in terms of its impact on circular economy (CE) indicators. Kunz et al. (2018) and Dubois (2012) highlight the challenges and potential inefficiencies of the EPR system, suggesting that a more comprehensive evaluation is needed to understand its overall effectiveness in promoting circular economy principles.

Therefore, this paper aims to evaluate the impact of the extended producer responsibility system on the circular material use rate in the manufacturing sector.

The paper is structured as follows: existing studies and theoretical frameworks related to EPR, and its impacts are examined in the literature review; the data collection and analysis methods used in this study, particularly the difference-in-differences (DiD) method are detailed in the methodological approach; the findings from the DiD analysis, highlighting the impact of EPR on circular material use rate are presented in the research results; the implications of the findings are discussed and directions for future research are suggested in the conclusion.

2. LITERATURE REVIEW

Since the United Nations adopted the Sustainable Development Goals (SDGs) in 2015, there has been an unprecedented focus on optimal production and consumption issues. Consequently, government bodies, international organisations, scientific institutes, and companies have aligned their strategic development plans with the SDGs. Raju & Prabhu (2018) noted that the principle of "doing more and better with less waste" has become a critical concern for business representatives today.

The consistent definition of the concept of responsible production still requires clarification. While some scientists associate responsible production with corporate social responsibility, the vast majority give priority to optimising production processes (Wang et al., 2019). Responsible production and consumption strategies differ in developed and developing countries based on economic conditions, demographics, and socio-cultural factors (Spaargaren, 2011; Zhidebekkyzy et al., 2023; Kalmakova et al., 2021).

Since the rapid development of production capacities has led to environmental degradation, the organisation of responsible production in developing countries such as China, Pakistan, and Vietnam is considered a "triple bottom line", that is, a way to solve social, environmental, and economic problems (Liu et al., 2021). Responsible production provides many advantages in long-term enterprises by saving resources, reducing costs, improving product quality, meeting modern requirements of society and consumers, and increasing social responsibility (Zarte et al., 2019; Baines et al., 2012; Musova et al., 2021).

Extended producer responsibility is a key policy for promoting a circular economy, shifting the burden of waste product treatment to different stakeholders and minimising total cost (Bin, 2005; Guo-peng, 2006). Governments play a significant role in perfecting this system, implementing green procurement, and advocating for green consumption (Xiang, 2012). Developed countries utilise EPR systems to increase recycling and material recovery rates systematically, incentivise manufacturers to adopt eco-design and sustainable production practices, and facilitate comprehensive waste management frameworks (Gui et al., 2013; Mayanti & Helo, 2023; Štreimikienė, 2023; Zielińska et al., 2023). Aa a result more sophisticated methods of consumption (such as conspicuous, green, and ethical consumption) become an essential constituent of new consumption culture (Baranowski & Kopnina, 2022) enhancing business innovations development in a responsible way (Oliinyk et al., 2023). In developing countries, the implementation of EPR and circular economy models faces challenges such as the low impact of waste minimisation projects, high implementation costs, and the need for industry competence in production process changes (Tahulela & Ballard, 2019; Zhidebekkyzy et al., 2022; Rabe at al., 2023). Overall, these systems are designed to promote a circular economy by holding producers accountable for the environmental impacts of their products throughout the product lifecycle, including end-of-life management.

EPR influences environmental indicators such as the circular material use rate, waste reduction, recycling rate, resource efficiency, and carbon emissions, encouraging manufacturers to reduce their environmental footprint. Economically, it affects cost indicators by reducing waste disposal and raw material costs, thus enhancing financial efficiency and competitiveness (Kaffine & O'Reilly, 2015; Zhidebekkyzy et al., 2022), which, in turn, positively affects the municipal waste management systems (Ginevičius, 2022). Additionally, EPR drives operational changes, including innovations in product design that facilitate easier recycling and reuse, aligning with circular economy principles (Ellen MacArthur Foundation, 2013). Implementing take-back schemes and improvements in waste management infrastructure are further operational adjustments prompted by these policies.

To investigate a firm's ability and propensity to innovate in green technology and implement EPR, Zhao et al. (2021) used variables such as firm size, firm age, number of employees, ownership structure, market outlook, firm revenue, and firm value. These control variables were selected to capture factors influencing EPR system adoption, ensuring that the observed impacts were specifically associated with the

EPR system and not with other business characteristics or external economic conditions. Zheng et al. (2017), in addition to the firm's financial performance, included EPR-related laws and regulations, corporate image, and executive consciousness as control variables to assess their impact on EPR adoption. The results highlight that these factors are critical to promoting EPR practices in the industry. This highlights the importance of analysing the financial performance of companies in the industry to assess the effectiveness of implementing the extended producer responsibility system.

The success of EPR-based environmental policies is contingent on different factors. Gupt & Sahay (2015) conducted a comparative analysis of the 27 selected cases of EPR in practice across three different types of economies – developed, developing, and developing with an informal sector. According to their research, the financial responsibility of producers and the establishment of separate collecting and recycling agencies significantly contributed to the success of EPR-based environmental policies. A range of studies are dedicated to the empirical evidence for the effectiveness of the EPR system. For example, Peng et al. (2020) used a difference-in-differences approach to identify the causal relationship between EPR and eco-innovation, finding that adopting take-back programs under EPR motivates producers to develop eco-innovation. Peng et al. (2019) utilised a game theory to establish an evolutionary game model between government regulatory departments and electronic and electrical product manufacturing enterprises. As a result, the probability of an enterprise undertaking extended responsibility gradually increased and stabilised with increased government supervision and punishment intensity. Lai et al. (2014) collected survey data from 134 manufacturing exporters in China to show a positive association of EPR practices with performance outcomes.

Researchers in Central and Eastern European (CEE) countries have extensively explored the impact of EPR on economic agents, emphasising the necessity for innovative production methods to achieve a sustainable balance in the economy-environment ratio (Caprita, 2019; Simionescu, 2023; Zvarych & Zvarych, 2019). Siuta-Tokarska et al. (2022) analysed the effectiveness of the EPR concept for packaging and energy sectors in transitioning to CE, with a specific focus on Poland's experience. According to Tsuskman & Dudina (2020), the proposed Concept of EPR in Hungary has numerous controversial issues and potential negative consequences, such as violating its and shifting financial burden to end consumers. Zoumpalova et al. (2023) argue that the Czech textile industry faces significant challenges transitioning to a circular economy, primarily due to several microeconomic, macroeconomic, technological, institutional, and data-related barriers. The findings of this study, based on questionnaires and in-depth interviews, show that measures such as excise taxes, extended producer responsibility (EPR), and increased fees/earlier prohibition of landfilling have been repeatedly highlighted as possible recommendations to improve the situation.

Additionally, effective implementation of EPR schemes has been shown to reduce the environmental footprint of single-use plastics significantly. Countries with robust EPR regulations report higher recycling rates and decreased plastic waste. However, while EPR schemes are present in countries selected for this paper's empirical analysis, they are often described as lagging or lacking ambition in implementing all the EPR measures mandated by the EU's Single-Use Plastics Directive (Seas at Risk, 2022). The report by the Rethink Plastic Alliance and the Break Free from Plastic movement highlights those countries such as Croatia, Slovakia, Bulgaria, Romania, and the Czech Republic are not demonstrating sufficient ambition and are overlooking key EPR measures. In 2018, Romania updated its EPR model via Emergency Ordinances, increasing company liabilities and penalties in the waste management sector, which led to higher costs and uncertainty. Consequently, many EPR schemes became reluctant to accept new clients or manage large waste volumes, challenging compliance and prompting efforts to align with EU regulations to enhance waste management and recycling (European Commission, 2018).

Most of these countries have implemented collective EPR schemes, some with centralised systems and others offering multiple options, requiring producers and importers to join and pay fees for managing and recycling packaging waste. However, the specific implementation models vary across the countries, and scientific literature particularly dedicated to impact assessment based on actual company data in the countries mentioned above appears to be scarce.

In summary, while the literature provides substantial evidence of the benefits and challenges of EPR systems in various contexts, there remains a gap in comprehensive empirical analyses of their impact on specific circular economy indicators, particularly within manufacturing enterprises.

3. METHODOLOGY

In the European Union, extended producer responsibility for specific industries has been gradually introduced over the years, mainly through specific directives targeting different product categories. The EPR system applies to 4 sectors of the manufacturing industry.

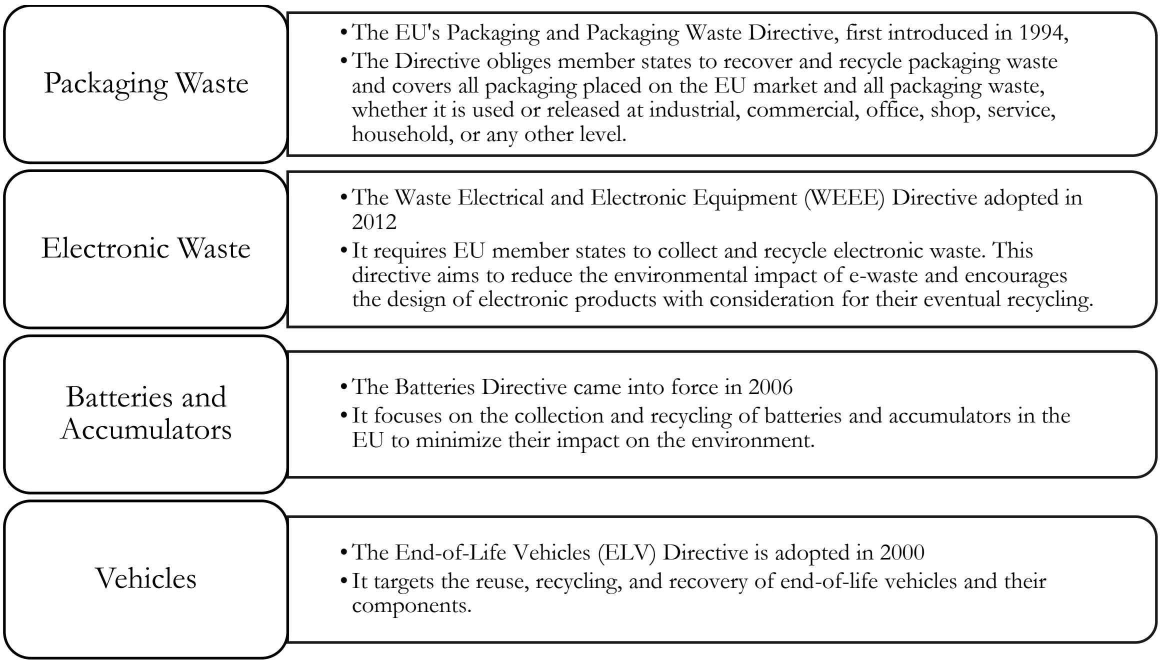

Figure 1. Industries with EPR in the European Union

Source: own compilation

Since The Waste Electrical and Electronic Equipment Directive was adopted later than all others, electrical and electronic equipment companies from seven Central and Eastern European countries were selected for analysis, particularly the Czech Republic, Poland, Slovakia, Romania, Estonia, Hungary, and Bulgaria. Since there are many companies in this industry, the following restrictions were introduced:

1) Considered companies created before 2010. This criterion ensures that the companies included in the study have been in operation long enough to have gone through both the pre- and post-implementation phases of the EPR directives. This allows for a more accurate assessment of the impact of these policies over time. Older companies are likely to have more established practices and available data, facilitating a clearer analysis of EPR-related changes.

2) Total operating income exceeds $150 million. By establishing a threshold level of operating income, the study focuses on larger enterprises, which are more likely to have structured environmental policies and the capacity to implement EPR-related processes. These companies also tend to have a greater environmental and economic impact, making their compliance with EPR systems more significant.

3) Companies with no official financial reports were excluded. Excluding companies without formal financial statements ensures that the analysis is based on verifiable and reliable data. Financial statements are critical to assessing a company's operating and financial health, and their availability demonstrates transparency and compliance with regulatory standards.

4) Companies that had significant omissions in their financial statements were excluded. Excluding companies with incomplete financial information prevents potential bias or inaccuracy in the study's conclusions. Significant omissions may indicate data quality problems and bias the analysis.

In total, 27 companies with a significant market share were selected. These companies make up the treatment group. Companies with the same criteria were selected as a control group. However, they are from other manufacturing industries not covered by extended producer responsibility.

Company data was collected from the global information and analytical database Emerging Market Information Service (EMIS) for 2010-2022. EMIS provides comprehensive company, industry, and country data, mainly focusing on emerging markets, and is widely used for financial and economic analysis.

The circular material use rate variable data for the same period were collected from the Eurostat database (Eurostat) in the Circular economy indicators section. Eurostat is the statistical office of the European Union, providing high-quality statistical information to enable comparisons between countries and regions.

To achieve the study's purpose, we have examined the effect of the EPR system on circular material use rate using a difference-in-differences (DiD) methodology.

DID is used to evaluate the impact of a policy, program, or any other intervention (in our case, The Waste Electrical and Electronic Equipment Directive) on a treatment group compared to a control group that was not exposed to it. This method controls for general time trends that may affect both the experimental and control groups equally. This helps ensure that the intervention causes changes in the dependent variable, not external factors (Zhao et al., 2021). Also, this method was chosen to solve endogeneity problems and accurately assess the impact of the EPR system in the electronics manufacturing industry on the circular material use rate in selected countries.

The basic regression function is given as:

$$cmur = \alpha + \beta_1 treat_i + \beta_2 post_t + \beta_3 treat_i \times post_t + \varphi X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \qquad (1)$$

where i is the firm, t is the time, $cmur$ is the circular material use rate, $treat_i \times post_t$ is the core variable. During the sample period, if enterprise i is from treatment group, then $treat_i = 1$, otherwise 0. Similarly, when $t \geq 2013$, the $post_t = 1$; otherwise 0. X_{it} are all the control variables; ε_{it} is a random error term. λ_i and μ_t represent fixed and time effects, respectively. The coefficient β_3 is the core estimated value. If it is significantly positive, it means that the EPR system helps to promote the circular material use rate.

A detailed description of all variables used in the analysis is presented in Table 1.

Table 1

Variable description

Variable type	Variable name	Variable symbol	Variable definition
Explained variable	Circular material use rate	*cmur*	The proportion of materials that are reused, recycled, or recovered from waste products concerning the total material use within an economy
Explanatory variable	treat*post	*treat*post*	According to the sectors of industry applying the EPR system and the promulgation time of the EPR system, the core explanatory variable (treat * post) was obtained
Control variable	Firm age	*age*	Sample period – establishment period
	Asset trend	*asset_trend*	Provide insights into a company's operational performance, investment strategies, and overall financial health
	Return on Assets	*roa*	Financial indicator that measures how effectively a company uses its assets to generate net income
	Earnings Before Interest, Taxes, Depreciation, and Amortization	*ebitda*	Provides a comprehensive view of a company's potential to generate cash from its core activities
	Debt-to-Equity Ratio	D/E	Financial metric used to assess a company's financial leverage

Source: own compilation

The circular material use rate (*cmur*) directly reflects the effectiveness of EPR systems in promoting a circular economy in the manufacturing sector, making it a critical metric for assessing the impact of EPR policies. Treatment and post variables (*treat*post*) indicate whether the company belongs to the treatment group (affected by the EPR) and whether the observation is carried out after implementing the EPR directive. This variable is important for determining the causal impact of EPR systems using difference-in-differences methodology, which compares changes over time between those exposed to the policy and those not.

The firm *age* variable is equally important because it controls firms' maturity and can influence their operational and environmental practices. *Asset_trend* variable provides insight into a company's operating performance and investment strategies, which can impact its ability to implement circular practices. Return on assets (*roa*) measures how efficiently a company uses its assets to generate revenue, potentially impacting its ability to invest in circular economy practices. Earnings before interest, taxes, depreciation and amortisation (*ebitda*) reflect a company's operating profitability, which can impact its financial ability to engage in responsible manufacturing practices. The debt-to-equity (D/E) ratio can influence a company's risk and investment decisions regarding environmental practices.

Taken together, these variables help isolate the EPR system's impact from other operational, financial, and economic influences, thereby allowing for a more accurate assessment of its effectiveness in increasing the circular material use rate.

The dependent variable *cmur* data were lagged by one year to account for time lags in exposure and avoid simultaneity problems.

Table 2

Descriptive statistics

Variable	Obs	Mean	Std. dev.	Min	Max
cmur	408	7,844	3,52	1,4	19,3
treat	408	0,794	0,405	0	1
post	408	0,75	0,434	0	1
*treat*post*	408	0,596	0,491	0	1
age	408	15,941	6,442	1	31
asset_trend	408	28,647	107,485	-78,18	955,92
roa	408	7,312	12,204	-88,79	66,01
ebitda	408	10,761	11,621	-38,51	91,17
D/E	408	258,955	169,65	-280,57	919,77

Source: own calculation

The results provided in Table 2 summarize key statistical measures for variables across a sample of 408 observations. The average circular material use rate is 7,844, suggesting that, on average, countries in the dataset utilize an average volume of materials in a circular manner (either through recycling, reusing, or recovery). The range from 1,4 to 19,3, and a high standard deviation indicates considerable variability among countries, implying that while some countries are highly efficient in circular material usage, others are much less so. As can be seen from Table 2, the variables *treat, post,* and *treat*post* are dummy variables that take the values either 0 or 1. The average firm age is around 16 years, which shows a mix of relatively young and mature firms, indicating a diversified sample of company lifecycle stages. The ROA suggests that while some firms are highly efficient in using their assets to generate profits, others struggle, showing varying operational efficiencies. Also, EBITDA values point to a varied financial performance, with some firms achieving high operational profits while others incur losses.

4. EMPIRICAL RESULTS AND DISCUSSION

According to regression model (1), the two-way fixed-effect model was used to test the impact of the EPR system on circular material use rate. The results are given in Table 3. Column I of Table 3 shows the regression results without control variables, and column II shows the regression results with control variables. After adding the control variables, the coefficients of *treat*post* decreased slightly but remained significantly positive. The influence of the D/E and *age* variables was found to be insignificant for *cmur*, for this reason they were excluded from the model.

Combined with descriptive statistics, implementing the EPR system increased the circular material use rate (*cmur*) by 10,5%. It was obtained by dividing the *treat*post* coefficient 0,824 by the descriptive statistical mean of *cmur* 7,844. It showed that the EPR system could effectively promote the circular material use rate. This effect holds even when controlling for various firm-specific variables, demonstrating a solid causal relationship.

The coefficient of variable *treatment was omitted due to multicollinearity, possibly because the main effect of treatment was* captured in interaction with the post-period. The *post* variable is significant in both models, indicating changes in the circular material use rate related to time.

The coefficient of variable *asset_trend* is negative and statistically significant at a 1% level, indicating that trends in asset management negatively correlate with circular material use rates. The negative association suggests that firms experiencing significant changes in asset values may be less focused or capable of implementing practices that enhance circular material use. This could be due to prioritising short-term financial stability over long-term sustainability practices.

Table 3

Results of Difference in difference analysis (independent variable – *cmur*)

	I	II
*treat*post*	1,001** (0,487)	0,824** (0,492)
treat	0 (omitted)	0 (omitted)
post	1,443*** (0,434)	1,217*** (0,449)
asset_trend		-0,003*** (0,0009)
ebitda		-0,019** (0,011)
roa		0,020** (0,01)
constant	7,358*** (0,171)	7,555*** (0,205)
Time effects	Yes	Yes
Firm effects	Yes	Yes
Number of observations	408	408
Number of groups	34	34
R^2	0,0687	0,098
F-statistic	F(2, 372) = 7,52 [0,0006]	F(5, 369) = 5,82 [0,0000]

Notes: 1) in parentheses, there are robust standard regression coefficient errors;
2) **, *** - significance of coefficients at 5% and 1% levels respectively.
Source: own calculation

EBITDA is negative and significant at a 5% level, suggesting operational profits before depreciation, taxes, etc., are inversely related to the circular material use rate. It might indicate that firms with higher operational profits could be investing less in sustainable practices, possibly due to a focus on maintaining financial performance metrics.

Return on Assets is positive and significant at a 5% level, implying better asset returns are associated with higher *cmur*. The positive relationship here suggests that firms with better returns on assets are more likely to invest in or benefit from circular practices, possibly due to better resource management.

Table 4

Skewness and kurtosis tests for normality

Variable	Obs	Pr (skewness)	Pr (kurtosis)	Adj chi2(2)	Prob>chi2
residuals	408	0,595	0,105	2,92	0,233

Source: own calculation

Since the value of the R-squared coefficient is quite low, we checked whether the distribution of model residuals corresponds to a normal distribution. The result of the Skewness and kurtosis tests showed that the distribution of model residuals corresponds to a normal distribution.

It should be noted that both models show robust overall model fit with significant F-statistics, suggesting the models are statistically significant at explaining the variation in circular material use rate.

Next, robustness tests were carried out to check the reliability and consistency of the results. For this purpose, Propensity Score Matching followed by Difference-in-Differences (PSM-DID) analysis was carried out. Not-treated enterprises were selected as the control group, and different enterprise characteristics were taken as the matching criteria. The results of kernel matching are shown in Figure 2. After matching, the gap between the treatment and control groups is significantly narrowed. It showed that the PSM could solve sample selection errors, and the PSM-DID method can be further used for robustness estimation.

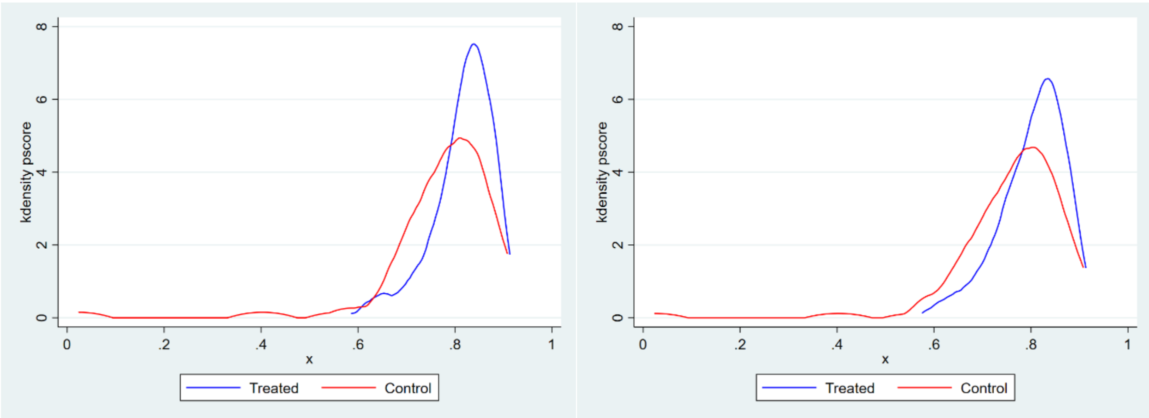

Figure 2. Kernel function diagram before and after matching

Source: own calculation

In the next step, we conducted a bootstrapping placebo test. Following Bradley et al. (2016), 100 samples were taken from all sample enterprises to randomise the impact of the extended producer responsibility system on specific enterprises, and regression was conducted according to the (1) model. After simulating 100 times, the pseudo-regression coefficient of the random sample was small, with a mean of 0,0003. Therefore, it further confirms that the conclusion is robust.

5. CONCLUSION

This study uses a difference-in-differences method to identify the effect of the EPR system on the circular material use rate in manufacturing enterprises. The empirical analysis considered data from 27 electronics manufacturing enterprises in the Czech Republic, Poland, Slovakia, Romania, Estonia, Hungary, and Bulgaria from 2010 to 2022. The results from the DID analysis demonstrate a statistically significant positive impact of the EPR system on the circular material use rate, with an average increase of approximately 10,5% in *cmur*. This effect is notably robust, as evidenced by consistent findings across multiple model specifications and the inclusion of control variables such as asset trends, return on assets and Earnings Before Interest, Taxes, Depreciation, and Amortization (EBITDA). This conclusion is still valid after a series of robustness tests.

The findings suggest that the EPR system effectively enhances circular material use within the electronics manufacturing industry, a critical sector in the context of environmental sustainability. Furthermore, this study highlights the necessity for continuous monitoring and evaluation of EPR systems to ensure their effectiveness and adaptability in evolving market conditions. Policymakers should consider integrating advanced data analytics and digital tracking technologies to enhance the transparency and efficiency of EPR systems. Encouraging stakeholder engagement and collaboration between manufacturers, consumers, and waste management entities will be crucial in overcoming implementation challenges and fostering a shared commitment to sustainability goals. Practitioners and policymakers could consider these results empirical support for expanding or intensifying EPR directives to other high-impact sectors. Such initiatives could significantly contribute to broader environmental goals, particularly within the circular economy framework.

Research limitations. The low value of the coefficient of determination was expected since the dependent variable circular material use rate is significantly influenced not only by microeconomic but also by macroeconomic indicators. For example, GDP, investment, environmental taxes and subsidies, international trade indicators, etc. However, the authors in this article did not aim to consider all kinds of factors influencing the dependent variable. The purpose of the article is to assess the impact of the extended producer responsibility system on the circular material use rate in the manufacturing sector using the example of a specific sample of companies. The significance of the F-statistic and skewness and kurtosis tests show that the model as a whole is statistically significant.

Depending on data availability, future research could examine the long-term impacts of EPR systems in other countries or sectors.

ACKNOWLEDGEMENT

This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP19576593).

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