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Ecological Innovations Supporting Sustainable Development: The Case of the Polish Tire Industry

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Abstract

Valuable eco-innovations are emerging through increasingly close collaboration between the scientific community, industry, the energy sector, and public institutions supporting research, development, and the commercialization of new technologies that address specific market needs. Today, the implementation of eco-innovations is a key factor across many sectors and constitutes a significant barrier to market entry. This study identifies the key drivers of the implementation of eco-innovation in the Polish tire industry, which ranks among the lowest in the EU in terms of the adoption of eco-innovation. Legal regulations—particularly those related to the circular economy and Extended Producer Responsibility (EPR)—emerged as the strongest drivers, as indicated by over 60% of the companies surveyed. Financial support and incentives, such as tax relief, were emphasized by 70% of respondents as crucial for accelerating eco-innovation. This study also highlights significant barriers, including limited access to capital (cited by 65% of respondents) and the high costs associated with eco-innovative methods. Green public procurement and the certification status were recognized as important, albeit less impactful, factors. Expert interviews confirm these findings, underscoring the need for improved public funding mechanisms and stronger legislative support to overcome the current stagnation. This research concludes that without such measures, progress in eco-innovation within the sector may remain slow, thereby hindering the achievement of sustainable development goals.

Keywords: tire industry; eco-innovations; development strategy; production model; tire recycling; legal requirements; key implementation factors

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1. Introduction

Globally, approximately 3 billion car tires are manufactured each year, from which about 1.5 billion worn tires are treated as waste. These tires are mostly used for passenger cars and trucks. Worldwide, the total quantity of end-of-life (ELT) tires is estimated to exceed 20 million tons annually, of which over 14 million tons are recycled [1–3]. Tires are among the most recycled and reclaimed products in the U.S. The utilization of end-of-life tires has been a priority for the U.S. Tire Manufacturers Association (USTMA) members for almost three decades. USTMA promotes market progress and advocates for federal and state regulations supporting sustainable tire recycling markets. The 2023 ELT Tires Management Report shows that approximately 79% of ELTs are recycled or reclaimed [1,2].

In the European Union, the generation of ELTs is estimated at 3.2 million tons per year, of which over half are recycled into materials and more than 30% are recovered as energy. The material recovery rates of ELTs are similar in the EU and globally (52% and 51%, respectively) [3,4]. According to data from 2018, Poland produces over 36 million tires per year [5,6]. Data from [3,5] indicate that only about 35% of tires produced are recycled, and 76.55% are reused. Market analyses of tire production show intensive development in both tire manufacturing and methods of utilization, driven by technological advances and ecological innovations [5–7].

Organizations operating in the tire sector strive to gain a competitive advantage by increasing economic and environmental efficiency and reducing production costs. Consequently, technological and organizational solutions take account of environmental, economic, and social conditions that can significantly affect how they operate. This concept continues to gain popularity and has been present for years in the scientific literature, legal acts, strategic documents, decrees, and directives [8].

The definition of eco-innovation is closely related to the definition of innovation [9], which, according to the OECD [10], refers to activities involving the implementation of a new or significantly improved product, technology, service, marketing, or organizational method in business practice. The main types of innovation are distinguished as product innovation concerning products and services, and business process innovation, which involves enterprise processes such as production, distribution, marketing and sales, information and communication systems, and administration and management [10].

Innovation is also sometimes defined as the introduction of a new product, service, production method, market, or organizational structure [11]. In a broader sense, innovation is perceived as a complex management process leading to the creation, development, and implementation of new solutions within the body that creates or introduces them [12]. Thus, innovation can be understood as a technological change that serves as a fundamental element in the business sector aiming to achieve success. The creation of innovation within an organization is based on the search for new information, knowledge, and solutions, supported by organizational systems, incentive structures, and internal communication and interpersonal relations [13].

The concept of innovation is closely linked to sustainable development (SD), integrating economic, social, and environmental aspects [14]. The element that connects innovation and sustainable development is eco-innovation [15], defined as any innovation that contributes to sustainable development by reducing the negative impact on the environment. Eco-innovation is an evolving concept closely related to the current state of knowledge in environmental protection and to objectives set at the organizational level, in government programs, and in strategies supporting sustainable development and environmental protection [16].

Eco-innovations implemented in the tire sector are economic, social, technical, and, most importantly, ecological [17]. The main objectives of introducing eco-innovations within organizations are: (a) reducing or eliminating negative environmental impacts, (b) improving economic outcomes, such as lowering operating costs, (c) enhancing the company's image among stakeholders, the public, and ecological organizations, (d) improving safety and working conditions, and (e) increasing the company's perceived value among current and prospective investors.

The determinants of eco-innovative activities in enterprises are defined as sets of external (exogenous) and internal (endogenous) factors that initiate the generation of new ideas and solutions and support the creation of inventions that mitigate negative environmental impacts [15]. External factors influencing eco-innovation include competitiveness, consumer expectations, environmental regulations, scientific and technological advances,

economic and social progress, and environmental changes [17]. Internal factors primarily relate to the management system within an organization, including ecological awareness and the aspirations of managers, voluntary commitments, environmental policies, and competition strategies [18,19]. The tire sector is developing dynamically, including both tire production and recycling activities. The tire market in Poland has undergone significant changes in recent years, with both declines and growth observed across different segments.

Tires produced from new raw materials, biodegradable tires, 3D-printed tires, and tires utilizing new technologies—such as self-repairing and air-purifying tires or those integrated with artificial intelligence—represent important elements of a modern, ecological, and innovative production sector. Conversely, new technologies and pro-environmental solutions enabling efficient recycling and waste management (used tires) stimulate the entire tire sector towards eco-innovative activities [3,6].

In the face of increasing regulatory pressure, rising consumer expectations, and growing environmental challenges, companies are progressively integrating eco-innovations as a key component of their development strategies. This trend is particularly relevant in the tire industry, which—due to its scale and environmental impact—plays a significant role in the broader industrial transition toward sustainable development.

This study aims to identify the key internal and external factors influencing the development of eco-innovation in the tire sector and analyze how these factors stimulate innovative activities aimed at reducing environmental impact.

The analysis encompasses both external factors—such as market competition, environmental regulations, consumer expectations, and technological progress—and internal factors, including the ecological awareness of managerial staff, competitive strategies, and internal environmental policies. Understanding the role of these elements enables a more accurate assessment to be made of what facilitates the effective implementation of eco-innovations and how this process can be enhanced in economic practice. The key determinants of eco-innovation include factors related to organizational characteristics, the adoption of technology, market-driven incentives, and current as well as anticipated environmental regulations [19–21].

The novelty of this publication lies in its comprehensive analysis of the factors influencing the development of eco-innovation in the tire sector—a field that, despite its increasing importance in the sustainable transformation of industry, remains relatively underexplored in the academic literature. The study considers both external drivers (such as regulations, competition, technological advances, and consumer pressure) and internal ones (including managerial awareness, environmental strategies, and voluntary commitments), as well as their interdependencies.

A distinctive feature of this study is its focus on the dynamically evolving tire market in Poland and its emphasis on the impact of modern technologies—such as biodegradable materials, 3D printing, artificial intelligence, and intelligent recycling management systems—in fostering environmentally friendly innovation. As such, this publication makes a meaningful contribution to the understanding of sector-specific eco-innovation and offers practical insights for policymakers and businesses aiming to advance sustainable development.

2. Methods

2.1. Description of the Polish Tire Market

The Polish tire market is divided into two demand categories, the Original Equipment Manufacturer (OEM) and Replacement segments, with the latter representing the larger share [5]. Several factors contribute to the prominence of the Replacement segment. Tire wear due to regular use necessitates periodic replacements, thereby driving demand. By tire type, the market is segmented into Radial and Bias (cross-ply) tires, which differ in their

fundamental structural composition and consequently in performance and application. Radial tires are constructed with layers of cords running radially from the center of the tire, offering enhanced stability, fuel efficiency, and a smoother ride. Bias tires, in contrast, feature crisscrossed layers of cords that provide increased durability and load-bearing capacity, making them suitable for heavy-duty applications [22–24].

By sales channel, the Polish tire market is divided into the Online segment and the larger Dealer/Exclusive Outlet segment. The latter benefits from a well-established presence, offering customers the ability to inspect products in person and receive expert advice from experienced staff.

Based on tube type, the market is categorized into Tube and Tubeless segments. Tube tires include an inner tube that holds air pressure within the tire casing. While historically widespread, their popularity has declined due to advances in tire technology. In contrast, the Tubeless segment has experienced substantial growth and modernization. Tubeless tires form an airtight seal against the rim, eliminating the need for an inner tube. This design offers several advantages, such as a reduced risk of sudden deflation, improved fuel efficiency, and enhanced overall performance.

Major players in the Polish tire market include Michelin, Bridgestone, Goodyear, Continental, Pirelli, Hankook, Dunlop, Nokian Tyres, Apollo Tyres, and Cooper Tires. To increase their market share, these companies are investing in innovation, strategic partnerships, and expansion initiatives [22,23].

In 2024, the Polish tire market began to show signs of recovery, with overall tire sales increasing. Growth was recorded in the passenger car, SUV, agricultural, and industrial segments. In the third quarter of 2024, the growth dynamics remained evident, particularly in the SUV, agricultural, and industrial sectors. Sales of tires for passenger cars and delivery vehicles also increased, while the truck segment remained stable. The only segment to experience a decline was motorcycle tires. These data indicate dynamic changes in the Polish tire market, with a clear rebound in 2024 after earlier declines, especially in the SUV, agricultural, and industrial segments [5,23]. Table 1 presents percentage changes in tire sales across various segments. Declines in 2022 and 2023 are visible, as well as a clear rebound in 2024, particularly in the SUV, agricultural, and industrial sectors.

Table 1. Development of the tire market in Poland, 2022–2024.

Tire Segment	2022	2023	2024	2024
	1	2	3	1–3
Cars	−4%	−14%	+9%	+3%
SUVs	+8%	−13%	+33%	+16%
Vans	−4%	−28%	+9%	−3%
Trucks	0%	−36%	+1%	−1%
Motorcycles	+4.8%	0%	−15%	−2%
Agricultural	−17%	−47%	+25%	+19%
Industrial	−11%	−28%	+20%	+23%
Summer	-	−24.3%	-	-
Winter	-	−11.9%	-	-
All-season	-	+1.8%	-	-

Tire recycling in Poland in 2022–2024 remained a key element of the environmental protection strategy, aimed at minimizing the impact of used tires on the ecosystem. In 2021, approximately 354.7 thousand tons more of tires were recycled compared to previous years [23,24]. In Poland, the Tire Disposal Center is the key company responsible for tire collection [20]. The basic fee in February 2024 was EUR 0.69 per tire. In 2021, approximately 252,600 tons of tires were put into circulation. The recovery rate was 74.7% and the

recycling rate was 44.5%, placing Poland among the European Union countries with lower tire recycling rates. For comparison, in Spain, the minimum recovery rate for used tires is 100%, of which at least 80% must be recycled and 20% used for energy recovery. In Slovakia, the minimum recycling rate is 75% and the recovery rate is 24% [22].

Poland produces approximately 300,000 tons of used tires per year, while its domestic processing capacity can handle over 400,000 tons, demonstrating untapped potential in this area. Additionally, 35,000 tires are illegally dumped in forests every year, posing a serious threat to the environment. Hence, it is necessary to increase the efficiency of the tire recycling system in Poland and to raise public awareness regarding the proper management of used tires [22]. These data emphasize the urgent need for actions to improve both the effectiveness of the tire recycling system in Poland and public awareness of responsible tire disposal. Figure 1 shows the level of recycling of used tires in Poland between 2015 and 2022.

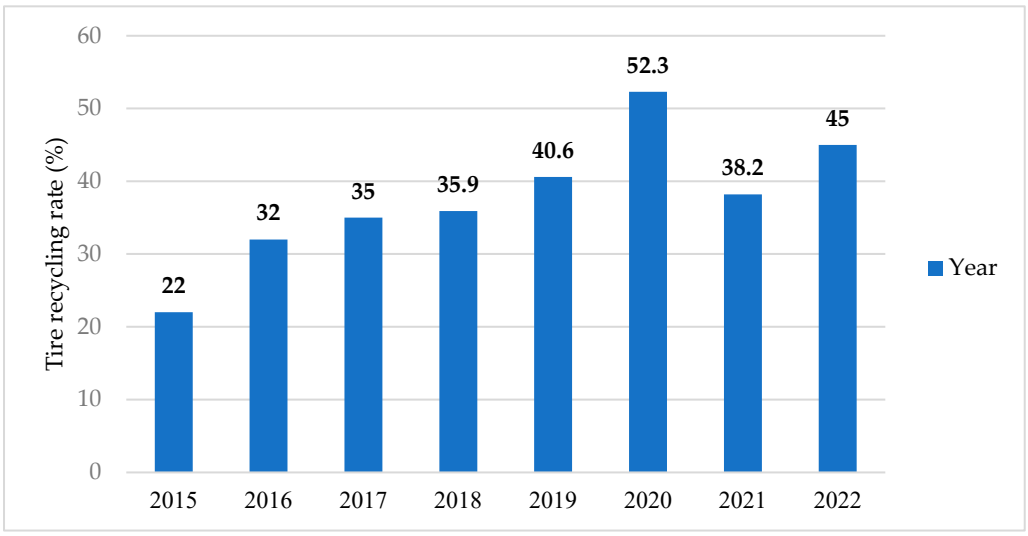


Figure 1. Recycling rate of used tires in Poland, 2015–2022.

Figure 2 presents a standard tire composed of several fundamental components, including rubber, steel wire, textile fibers, and various chemicals that ensure appropriate hardness, durability, and grip. The primary rubber materials are blends of natural and synthetic rubber, enriched with additives such as carbon black, oils, and antioxidants to improve performance and longevity [3,23,24].

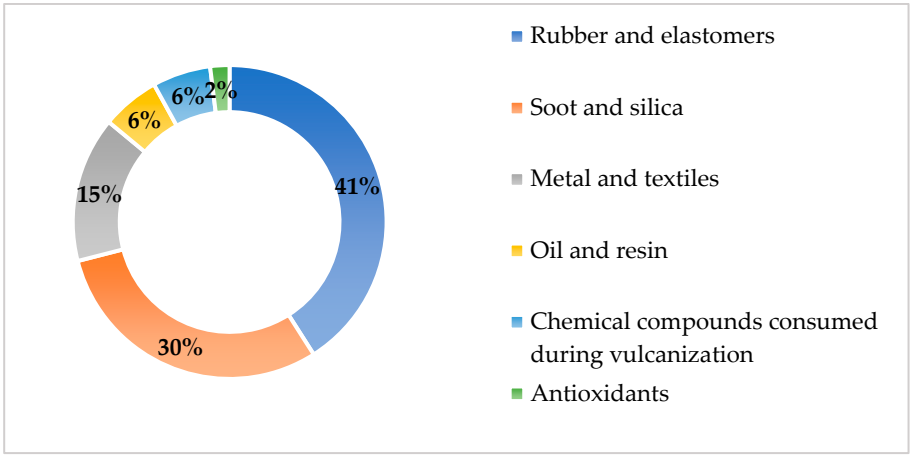


Figure 2. Percentage composition of materials used in tire production.

In tire production and its subsequent management, new technologies and an ecological approach are combined. Eco-innovation for tire design refers to their construction, new types of raw materials for production, and new manufacturing technologies. The development of green tires and processing methods and the use of sustainable materials form important trends for the future of the tire industry, and many tire companies have proposed their visions for the development of ecological tires. Rubber, cord fabric, and additives are the main materials used in tire production. Research is being developed on green materials that can meet the requirements of environmental friendliness and sustainable development, replace traditional materials, and decrease the consumption of petroleum resources in existing tire production.

These materials generally encompass natural or bio-based synthetic rubber, green renewable cord fabrics, and auxiliary raw materials used in manufacturing [24]. The Polish tire sector has significant potential but, due to its specific character, increasing competitiveness is only possible through eco-innovations. The circular economy (CE) can significantly influence the shape and development prospects of the sector, stimulate the activity of enterprises, and improve their competitive position. The implementation of the CE model requires long-term strategies in terms of sustainable resource consumption, the development of processing eco-innovations, and economics [6]. In this respect, the leading branches of the tire sector could develop innovative solutions and technologies that allow for the inclusion of more materials from renewable sources in tire production and, above all, extend their service life. All these activities will generate new CE business models and contribute to sustainable economic development.

2.2. Data Collection Methods

This work uses data triangulation [25,26], as this method allows for the research topic and phenomenon to be studied from several perspectives and with several data sources or methods. It aims to create a convergent and in-depth understanding of the topic by examining it from different perspectives. Figure 3 summarizes the tools used in the research process.

An analysis of the literature and documents was the first stage of this research, which identified the factors behind the implementation of eco-innovations in the tire sector. The analysis of the literature used bibliographic data and citations of articles indexed in selected scientific publications. The basis was literature databases [27,28] and a database of the content of Polish technical journals. First, the criterion for searching texts that met the assumed requirements was established, i.e., searching for texts published in the last 5 years and those that contained the phrase "eco-innovations" in the title. This identified over 200 scientific publications that corresponded to the criteria, which were then selected. The analysis of documents consisted of identifying environmental reports of companies in the tire sector in Poland. The reports were verified in terms of the environmental eco-innovations that had been implemented.

In the next stage, a survey questionnaire was developed. First, a set of questions was prepared, providing potential opportunities to obtain responses to the questions connected to the specific objectives of the work being conducted. The questionnaire that was developed was divided into three parts. The first part was devoted to essential data about the enterprise being studied, the second concerned the eco-innovations implemented, and the third concerned factors and barriers linked to the activities related to eco-innovations that were carried out. This study involved 9 companies operating in tire recycling (95% market share), 4 companies producing tires (100% market share), and 2 recovery enterprises. Of the 15 individuals participating in this study, 6 were members of company management staff, and 9 were employees of environmental protection depart-

ments. The third stage of the research process involved submitting the material collected for expert review by specialists in environmental activities and innovation within the tire sector. The target group was carefully selected based on their expertise in the subject matter, extensive experience in the tire industry, and ongoing collaboration with the sector. Five experts participated in this phase of the study.

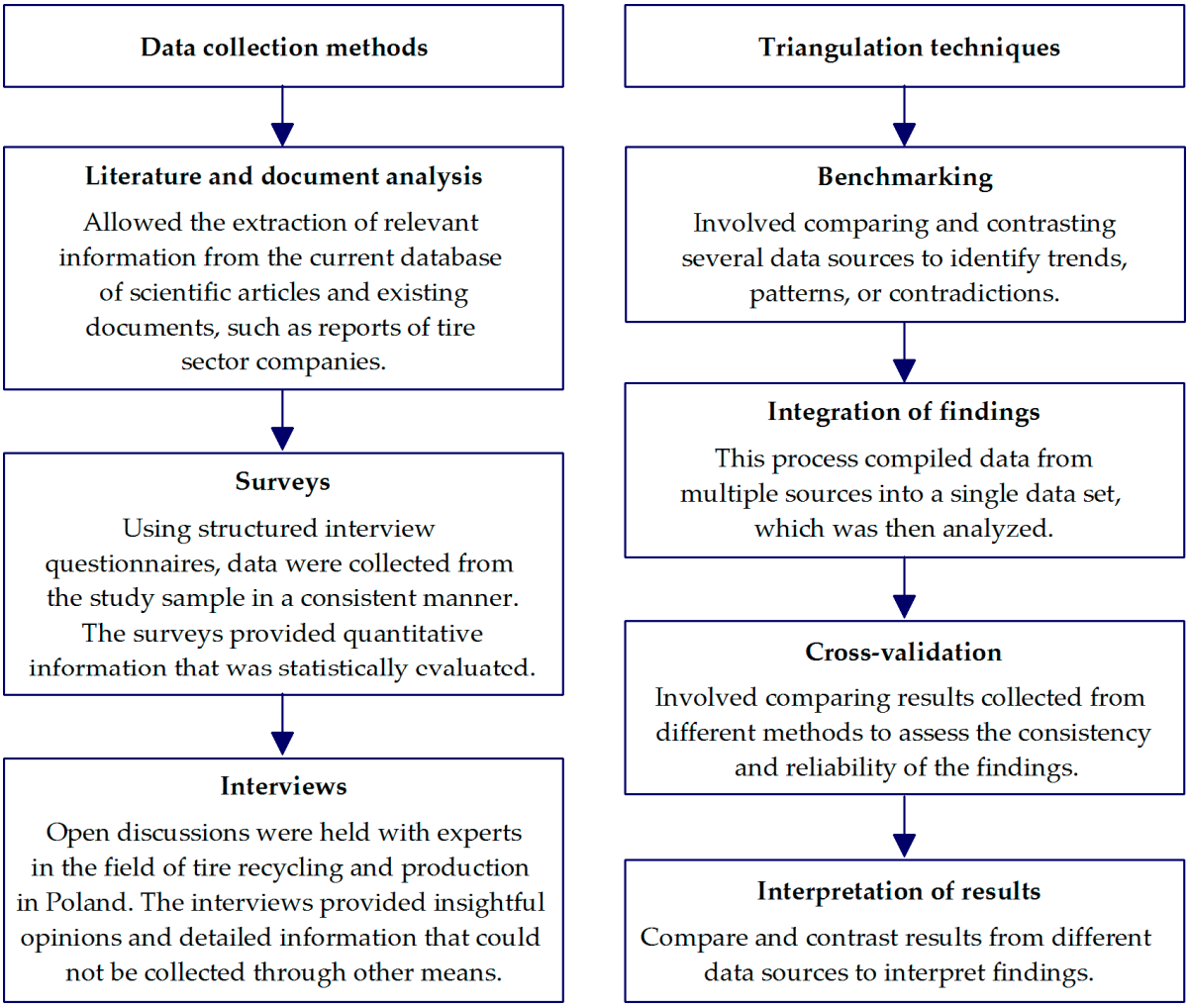


Figure 3. Diagram of the research process: Data collection methods and triangulation techniques.

In the qualitative part of the research, both content analysis and thematic analysis approaches were employed. Document analysis involved a systematic review of over 200 scientific publications and environmental reports issued by companies in the Polish tire sector. These documents were coded using pre-established categories related to carrying out eco-innovation (e.g., technologies used, sustainability indicators, and circular economy strategies).

In addition, responses to the open-ended survey questions and expert interviews were analyzed thematically. Thematic analysis was conducted in accordance with the six-phase procedure proposed by Braun and Clarke [29], which includes data familiarization, initial coding, theme generation, theme review, and narrative production. Following this methodology, we applied inductive coding to identify recurring themes related to eco-innovation drivers, barriers, and policy expectations. The coding process was carried out manually by two researchers to ensure consistency and reliability. Key themes identified included financial support mechanisms, regulatory constraints, and limited consumer awareness.

The integration of content and thematic analysis provided a robust triangulation of data sources and allowed for deeper insights into the structural and organizational conditions influencing the development of eco-innovation in the Polish tire industry.

The selection of economic and environmental indicators for this study was guided by four main criteria:

- *Relevance to the tire sector and eco-innovation goals*: Indicators were selected based on their direct connection to sustainable development challenges and opportunities in the tire industry, particularly concerning eco-innovation, implementation of the circular economy, and material recovery processes.
- *Data availability and reliability*: Only indicators with accessible and verifiable data—sourced from companies' environmental reports, national databases, or EU statistics—were considered. This ensured the credibility and comparability of results.
- *Alignment with international sustainability frameworks*: Priority was given to indicators consistent with recognized standards, including the Global Reporting Initiative (GRI) environmental performance indicators [30], ISO 14001 environmental management principles [31], EU Circular Economy Action Plan metrics for resource efficiency and recycling [7], and benchmarks from the European Tyre and Rubber Manufacturers' Association (ETRMA) [32].
- *Use in prior scientific research* [3,6]: The selected indicators were validated against the academic literature addressing eco-innovation and sustainability performance in industrial sectors, ensuring methodological consistency with earlier studies.

Based on these criteria, the following economic indicators were selected: cost of implementing eco-innovation measures, production efficiency, return on investment, and changes in market share. The environmental indicators included the recycling rate of used tires, recovery rate relative to national targets, use of sustainable or alternative raw materials, and potential for CO_2 emissions reduction.

3. Results

3.1. Identification of Factors Important for Implementing Eco-Innovations

Eco-innovations constitute a foundational element of the European Union's new development paradigm. A review of EU and regional strategic documents reveals numerous provisions aimed at promoting and supporting eco-innovation. The introduction of eco-innovations is still not common practice, despite the knowledge of the need to decrease the negative influence of processes and products on the environment. Eco-innovations are a proposal for a new development model for the Polish tire industry [33–35]. However, Poland is one of the lowest-ranked EU countries in terms of eco-innovation. The reasons for this are primarily the lack of an effective system for supporting and financing eco-innovations from public funds and the low knowledge of entrepreneurs about the benefits of their implementation. The expansion of the tire sector, together with ecological and innovation policy, should support the development of eco-innovations and encourage investors to seek eco-innovations.

Key factors important for the implementation of eco-innovations in the tire industry were selected and compared with the outcomes of this process in terms of legal and technical conditions, as shown in Figure 4. Additionally, the microeconomic calculation of investment profitability combined with the creation of an ecological image of the enterprise is presented in Figure 5.

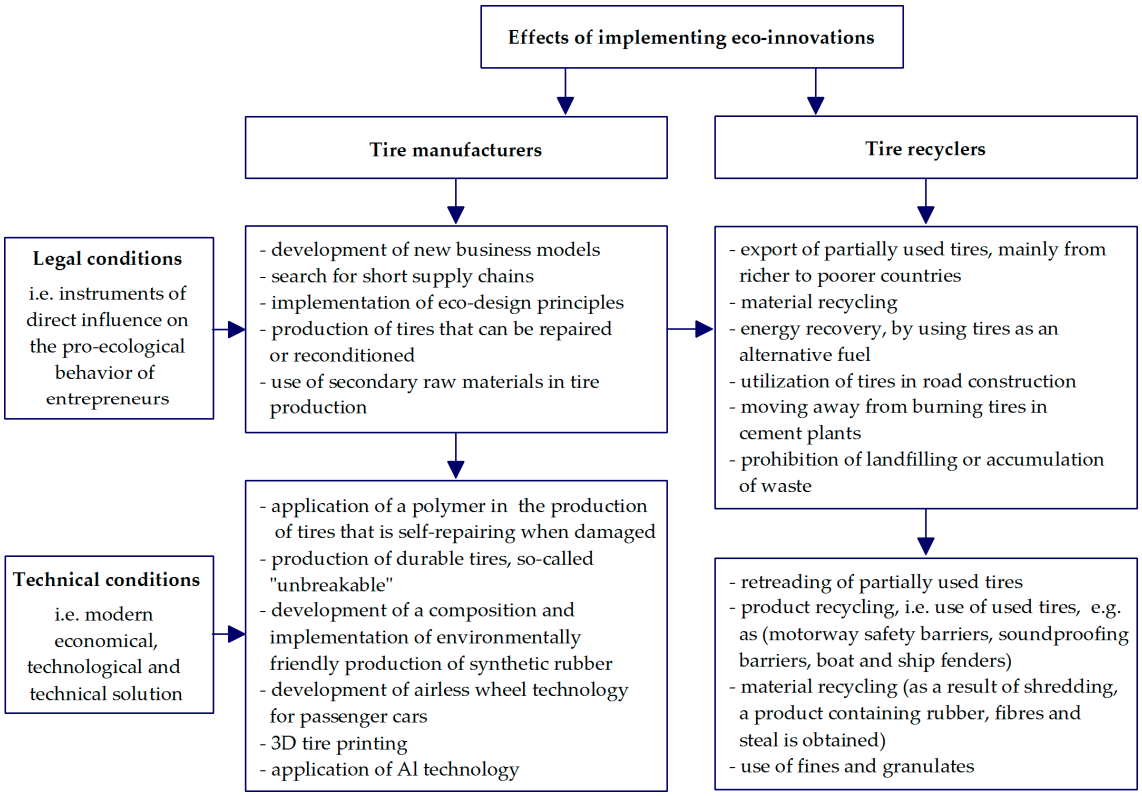


Figure 4. Legal and technical conditions as factors favoring the implementation of eco-innovations in the tire sector.

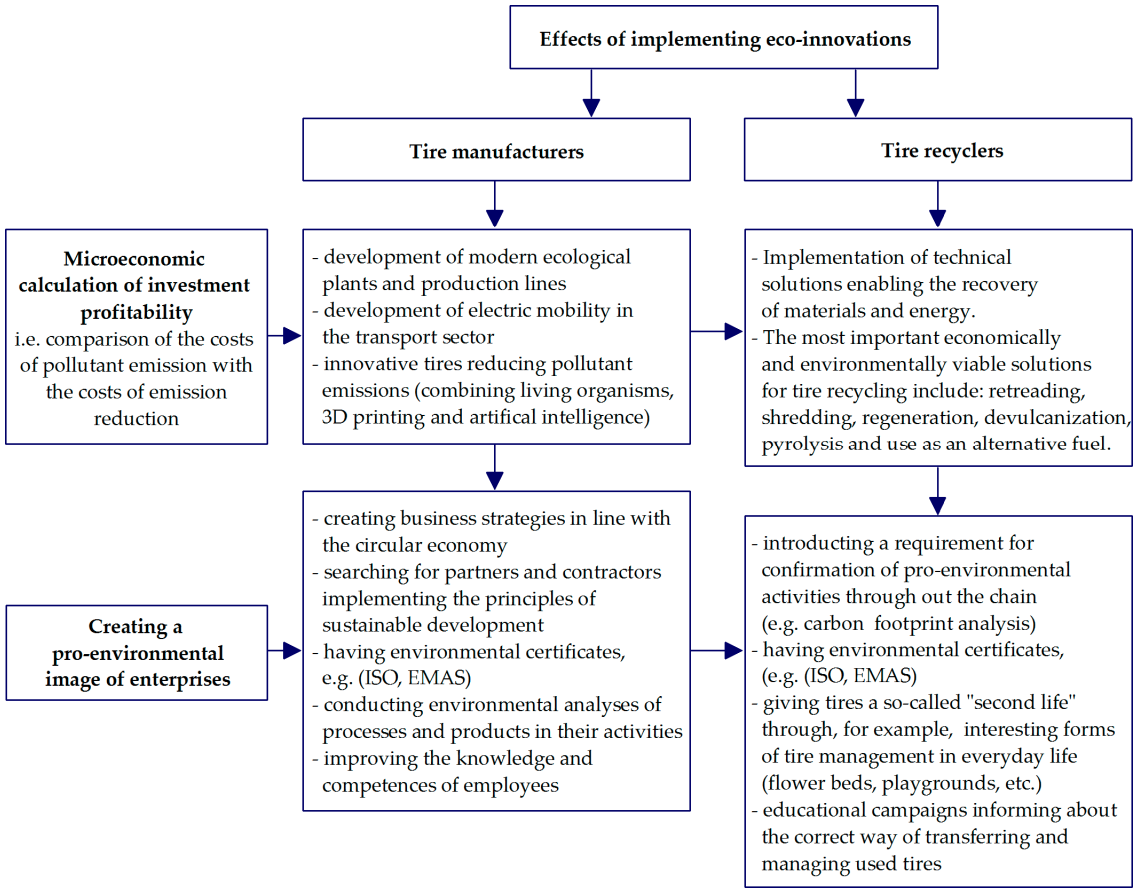


Figure 5. Microeconomic calculation of investment profitability and creating an ecological image as factors favoring the implementation of eco-innovations in the tire sector.

The material analyzed shows that the greatest force stimulating the implementation and development of eco-innovations, both among tire producers and recyclers, is legal regulation. The introduction of the circular economy (CE) concept into legal regulations has compelled the entire tire industry to undertake ecological actions, as presented in Table 2.

Table 2. Expected trends in the development of eco-innovations in the tire sector.

Criterion	Expected Trend of Eco-Innovation Development
Legal conditions	Increased development of eco-innovations due to the implementation of new legal regulations, e.g., Extended Producer Responsibility (EPR).
Technical conditions	Maintaining technological eco-innovations at the current level due to high costs and the availability of new technologies for tire production and recycling.
Microeconomic calculation of investment profitability	Increased eco-innovations because entrepreneurs have seen the possibility of reducing operating costs by investing in ecological solutions.
Creating an ecological image of enterprises	Decrease or maintenance at the current level because it is not a key factor driving the development of eco-innovations.

The eco-design directive introduced in the EU countries [34] and national waste management regulations specifying the recycling level [35,36] have led to eco-innovation developments in the tire sector. However, it should be noted that eco-innovations, due to their complex nature and the need to combine innovation and ecological policies, encounter barriers and hinder rapid development. Hence, it is necessary to develop an effective system for supporting and financing eco-innovations from public funds, combining new financial instruments with legislative guidelines. The most significant barriers to implementing ecological innovations are

- Lack of financial resources and difficulty accessing capital;
- Fairly significant costs of eco-innovative methods;
- Risk of market failure (no return on implementation costs);
- Deficiency of economic and tax stimulations;
- Increased competition;
- Administrative barriers, such as public procurement;
- Insufficient knowledge about environmental protection, the influence of the company's activities on the environment, and the economic benefits resulting from eco-innovations (currently, most entrepreneurs perceive ecological innovations from the perspective of high costs).

It is important to identify eco-innovative activities and monitor whether their implementation is in line with the assumptions (economic profitability throughout the value chain, i.e., searching for win–win solutions to minimize resource consumption).

3.2. Identification of Factors in Favor of Implementing Eco-Innovations Based on the Surveys Conducted

The survey aimed to identify factors that may encourage companies to implement eco-innovations. The respondents considered the following as significant conditions encouraging the implementation of eco-innovations:

- Increasing the recovery limit, which it is possible to achieve, especially for tire recyclers;

- Financial support;
- Green public procurement;
- Certifications;
- The responsibility of state bodies for implementing eco-innovations in organizations.

Increasing recovery limits is proposed, especially by tire recyclers, because this factor may affect the development of new technologies, and their introduction will stimulate the implementation of eco-innovations. The respondents pointed out that it is important to introduce financial incentives in the form of, for example, reliefs for companies implementing eco-innovations. Recyclers generally lack the so-called "financial bonus" (i.e., an incentive) as compensation for actions taken for the benefit of society and climate improvement. According to the enterprises surveyed, they should be provided with economic support from the sector in the development of eco-innovations. Green public procurement may also be one of the factors encouraging the tire industry to implement eco-innovations, but it should be much more widespread and promoted. In the tire sector, the appropriate certification and status of a product made from waste will also act as a support for eco-innovation. For some respondents, the status of waste is inappropriate for a product element made from recycled raw material. According to them, it should also have the status of a product.

Respondents indicated that state authorities are responsible for the progress of eco-innovations in Poland and activities that have an advantageous influence on the development of the entire tire sector. Some respondents believe that sustainable development and pro-environmental activities are the responsibility of the companies themselves, scientific units, and society.

The innovative activity of a company is identified as the ability to constantly search for, implement, and disseminate innovations accepted by potential consumers (end recipients). Both recyclers and manufacturers considered financial incentives, e.g., tax relief or rewarding innovative companies, to be the most important factor accelerating the implementation of eco-innovations. It is important, as the respondents pointed out, that their efforts in this area are appreciated by, for example, state authorities. Green public procurement was also considered a tool for shaping new standards for products and services, as well as a determinant of the goods, technologies, and innovations manufactured by companies. At the same time, the introduction of green public procurement will be a driving force for the development of eco-innovation in companies. The respondents indicated that having certificates was important as a stimulus for putting the principles of sustainable development into practice. The respondents placed significant emphasis on the responsibility of state authorities for implementing eco-innovations in organizations. Figure 6 shows the percentages of the most common answers regarding factors encouraging the implementation of eco-innovations in the organization.

The most significant issues identified by the group that was interviewed concern factors related to financial support, particularly in the form of tax relief and financial incentives, such as for implementation and investment projects. An increase in waste recovery limits was also noted as important among recyclers. Eco-innovations and certifications were regarded as stimuli for the implementation and promotion of green public procurement. Conversely, state authorities are most often held responsible regarding legal regulations aimed at stimulating the progress of eco-innovations in the tire sector.

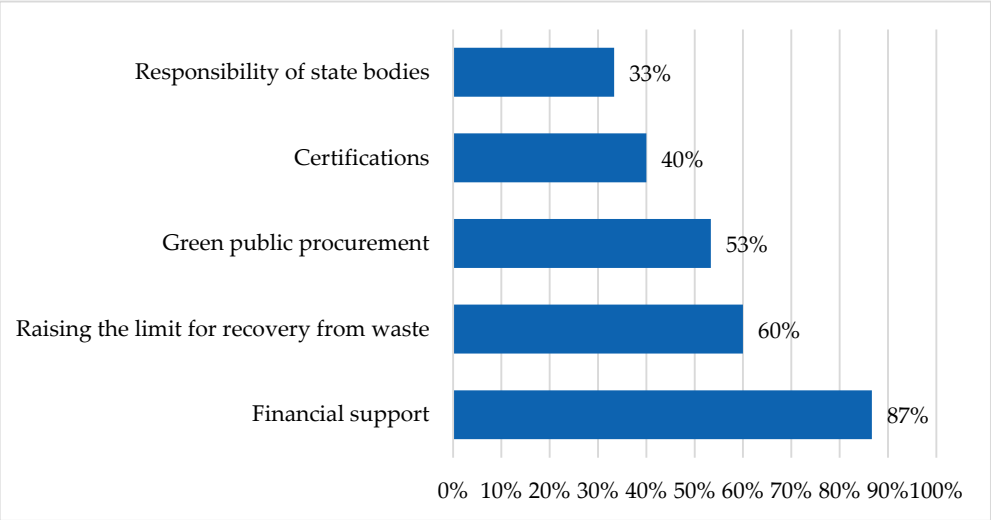


Figure 6. Percentage distribution of the most common opinions regarding factors encouraging the implementation of eco-innovations among tire enterprises.

3.3. Identification of Factors Influencing Eco-Innovation Implementation Based on Expert Interviews

The next stage of the research involved conducting a focused group interview (FGI) to verify the findings obtained from the in-depth interviews. The target group was selected very precisely based on their knowledge, extensive experience in the tire sector, and cooperation within it [37]. A Likert scale [38], the most commonly used tool for measuring attitudes, was employed to allow for the capture of many aspects of the phenomenon being studied. A five-point ordinal scale was used: 1—strongly disagree, 2—disagree, 3—neither agree nor disagree, 4—agree, 5—strongly agree.

The study results, showing factors impacting the achievements of eco-innovation in the tire sector, were discussed and assessed. Table 3 and Figure 7 present expert opinions and evaluations regarding these factors.

Table 3. Expert opinions on factors influencing the development of eco-innovations in the tire sector.

The Goal of the Study	Selected Quotes from Experts
Assessment of factors influencing the development of eco-innovations in the tire sector	[E1] "The awareness of entrepreneurs in the field of circular economy and available solutions affects the possibility of their creation and implementation. Awareness largely determines the openness and demand for this type of eco-innovation, which is why it is necessary to introduce appropriate financial instruments" [E2] "At the level of large companies, no one will allow themselves to depart from this trend of eco-innovation, or this trend may slow down a bit. But there will be no turn in the other direction." [E5] "Support instruments may be related not only to the implementation of specific technologies, there may also be innovations related to changes in business models—by promoting resource-efficient enterprises [E2] "To stimulate innovation in this area, appropriate incentives are necessary and all initiatives should be promoted" [E1] "Recovery limits are a secondary issue, they will not affect the development of eco-innovation" [E5] "It is important to encourage the entire sector, reliefs and preferential loans are a good direction"

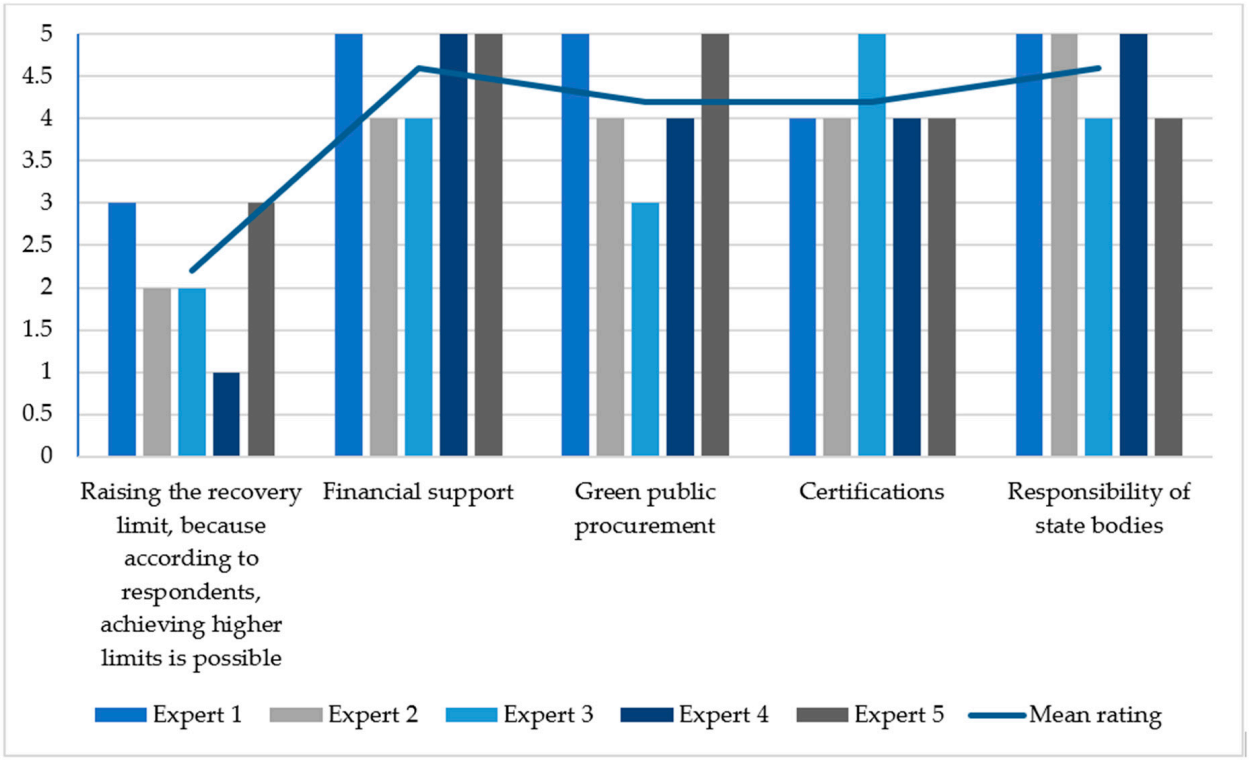


Figure 7. Expert assessment of factors influencing the implementation of eco-innovations in the tire sector.

Experts indicated that financial support for companies is essential if they are to put new, environmentally and economically friendly solutions into practice. They also highlighted the country's still very low eco-innovation rate, attributing it to the lack of appropriate incentives. According to the experts, all initiatives related to eco-innovation, especially green public procurement and certification, should be introduced and supported. State authorities are largely responsible for the current situation, and if no changes occur in this area, the entire economy's progress may be slowed down. One interview participant stated that increasing recovery limits would not significantly accelerate the implementation of eco-innovation in the tire industry.

4. Discussion

The study results indicate that financial support is one of the most significant factors driving the development of eco-innovations. Green public procurement and product and company certification rank slightly lower in importance. Activities by state bodies, particularly in terms of their responsibility for promoting eco-innovation within the economy, are considered less influential. Measures aimed at increasing waste recovery targets are ranked the lowest. The ranking is presented in Table 4.

Companies in the tire industry are already implementing advanced technological solutions, including nanotechnology and biotechnology, to reduce fuel consumption and pollutant emissions. However, challenges related to recycling end-of-life tires highlight the necessity of incorporating environmental considerations during product design. Recyclers, in turn, are compelled to develop new technologies that minimize environmental degradation. Despite recognizing the potential of eco-innovations, respondents emphasize the lack of appropriate systemic drivers and financial support, which hinders the growth of this sector [39].

Table 4. Rank of factors stimulating the development of eco-innovations in the tire sector.

Rating Type	Producer Rank	Recycler Rank	Expert Rank	Overall Rank
Raising the waste recovery limit	5	2	5	**4.0**
Financial support	1	1	1	**1.0**
Green public procurement	2	3	2	**2.3**
Certifications	2	2	3	**2.3**
Responsibility of state bodies	4	3	4	**3.7**

The tire industry is actively working on "green tires" using alternative raw materials, such as silica instead of carbon black, and plant-based or synthetic compounds that contribute to reducing oil consumption and CO_2 emissions. Nevertheless, a research gap remains regarding the actual impact of these innovations on micro-particle emissions and chemical substances from tires. Additionally, sufficient data on their durability and cost-effectiveness compared to traditional tires are lacking, which may limit commercialization and consumer acceptance [40–42]. Therefore, developing concepts for new materials and innovations, along with environmentally friendly and cost-effective methods for rubber recycling, represents one of the greatest environmental challenges of the 21st century [43–45].

Significant legal regulation barriers for recyclers include high environmental requirements (e.g., meeting specific standards and emission levels) coupled with low waste recovery limits in Poland. Recyclers are capable of achieving much higher recycling rates than legally required; however, due to the low recovery targets, they struggle to secure sufficient quantities of waste tires domestically. Consequently, recovery organizations consider importing raw materials from abroad to maintain their operations. Recyclers have highlighted the stringent environmental standards, high emission requirements, and necessary certifications as barriers to implementing ecological innovations [3,5].

Sustainable Tire Composition [23,45] is the first step towards creating eco-friendly tires by using alternative raw materials. Manufacturers are exploring synthetic blends, often incorporating silica, as a replacement for traditional rubber. The overall construction of the tire—from treads to sidewalls—is crucial for maintaining eco-friendliness. Furthermore, a more robust tire structure improves vehicle stability, enhancing overall performance and safety. Proper tire selection and maintenance can extend the tire life, thereby reducing waste and the frequency of replacements [46–48].

When analyzed in terms of *Sustainable Tire Management Systems*, tire recycling processes—such as collection, sorting, shredding, steel separation, granulation, and purification—are well-developed and enable material reuse in various sectors, including construction and as industrial fuel. However, this process is costly and requires continuous investments in technology, underlining the need for stable financial and regulatory support [48–51]. Moreover, tire recycling programs [46,47] are gaining momentum, with several manufacturers incorporating recycled materials into new tires [52,53].

Approximately 20–30% of greenhouse gas emissions in the automotive sector originate from tire production and use. Implementing a Sustainable Development and Circular Economy (CE) model in this sector requires effective collaboration between science and industry, alongside adherence to the 7R principles (reduce, reuse, recycle, etc.) [54,55]. In practice, however, legislative and organizational barriers—particularly related to increasing recovery and recycling targets—impede the implementation of such models.

Eco-innovations in the tire sector are increasingly important from both environmental protection and business competitiveness perspectives [56–58]. These factors condition the implementation of eco-innovations. Government support through funding and credit facilities is essential but should be better tailored to company needs and aligned with

international regulations. Green public procurement can be an effective tool for creating demand for innovative products; however, clear criteria and enforcement mechanisms are required. Product and process certification play significant roles in building trust and a market advantage but remain undervalued by many producers and consumers.

Despite technological progress and growing interest in eco-innovations, a significant gap persists between their potential and actual levels of implementation. Financial support remains the main factor determining innovation success, highlighting the need for systemic changes in public policy. Insufficient government engagement and coordination, along with a lack of effective incentive mechanisms, limit the scale of sector transformation. Furthermore, limited consumer awareness and knowledge about the ecological and economic benefits of "green" tires hinder market growth. Finally, legislative barriers related to recovery and recycling targets should be prioritized to accelerate the implementation of the circular economy model [55,56].

An integrated approach combining financing, regulation, market education, and technological innovation is crucial in order to effectively develop eco-innovations in the tire sector, benefiting both the environment and the economy. Financial support is the primary factor stimulating eco-innovation development in the tire sector. However, a clear lack of systemic incentives and adequate support hinders the full potential of these innovations. Compared to existing studies, our findings confirm commonly known barriers to implementing ecological innovations while additionally emphasizing the specificity of the tire industry, where issues related to tire design for recycling and effective waste management remain insufficiently addressed.

Moreover, our analysis shows that despite the implementation of advanced technologies and eco-friendly materials, practical limitations arising from legal regulations, insufficient financial incentives, and the complexity of recycling processes prevent the sector from achieving its full environmental potential. In that context, this study offers a new perspective on the complexity of tire lifecycle management and the need for an integrated approach combining technological innovation, legal frameworks, and economic support mechanisms.

5. Conclusions

In the EU countries, increasing attention is being paid to the innovation of companies that generate large amounts of waste and use large amounts of primary raw materials. This is necessary in a situation of increasing market needs and limited access to raw materials. Valuable eco-innovations are increasingly created thanks to cooperation between the world of science, the tire industry, alternative energy, and public institutions supporting research and development. Thanks to this cooperation, innovations and new technologies have practical applications that meet specific market needs and requirements.

Eco-innovations are a basic tool with which entrepreneurs from the tire sector can increase the company's competitive potential and improve its place in the environment. Implementing eco-innovations is a key issue in many industries and a specific barrier to entry. However, smaller companies, especially recyclers, have problems with generating innovative solutions, mainly due to the level of knowledge and technological advancement.

Legal and regulatory frameworks are the primary drivers of eco-innovation in the Polish tire sector, with over 60% of companies indicating these as the main stimulating factor. Financial incentives, including tax reliefs and preferential loans, were identified by approximately 70% of respondents as key to fostering eco-innovative investments. Major barriers include limited financial resources (noted by 65% of companies surveyed), high implementation costs, and administrative obstacles. While green public procurement and product certification support eco-innovation, their influence remains moderate and requires

wider adoption and promotion. Expert opinions emphasize that without enhanced financial and legislative support, Poland's tire industry will continue to lag in eco-innovation, risking slower overall economic and environmental progress.

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