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FACTORS FACING THE IMPLEMENTATION OF ECO-INNOVATIVE SOLUTIONS IN CITIES IN POLAND – A REVIEW OF LITERATURE AND GOOD PRACTICES

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Purpose: The paper examines the role of eco-innovations in driving sustainable urban development in Poland. It identifies institutional, financial, and social factors that determine their implementation and presents good practices from major Polish cities. The study expands current knowledge by linking eco-innovation with governance capacity, citizen participation, and adaptive urban management.
Design/methodology/approach: A triangulated analysis combining literature review, EU and national policy documents, and case studies from selected Polish cities was conducted. The comparative and desk research methods enabled the integration of theoretical frameworks with practical insights.
Findings: The research reveals that the effectiveness of eco-innovation in Polish cities depends on the integration of legal frameworks, financial mechanisms, and public awareness. Successful cases (Warszawa, Kraków, Łódź, Wrocław, Rzeszów, Gliwice) show that combining technological, social, and organizational innovation enhances environmental performance, resilience, and quality of life. The study provides new evidence that strengthening institutional capacity and citizen engagement accelerates green transformation.
Practical implications: The findings support urban policymakers and practitioners in designing coherent strategies that connect financial instruments, certification systems, and education to foster sustainable urban governance.
Social implications: By emphasizing participatory and educational dimensions, the study demonstrates how eco-innovation builds environmental awareness, promotes social inclusion, and enhances local resilience to climate change.
Originality/value: This paper offers an integrated framework linking policy instruments with practical applications of eco-innovation in Polish cities, contributing to the understanding of how institutional and social mechanisms shape sustainable urban transitions.
Keywords: eco-innovation; sustainable development; urban policy.
Category of the paper: Conceptual paper.

1. Introduction

1.1. Environmental challenges and the need for sustainable urban development

Modern cities are facing increasingly complex and interconnected challenges, resulting from both growing demographic pressure and deepening environmental, infrastructural and economic problems. On the one hand, there is a systematic increase in the urban population, which is the result of urbanization processes and internal migrations, leading to an increased concentration of population in the largest centers. On the other hand, many European societies – including Poland – are experiencing an ageing population, which forces urban infrastructure, public services and social space to adapt to the needs of older people (Główny Urząd Statystyczny, 2023; United Nations, Department of Economic and Social Affairs, 2019).

The increase in the number of people in cities directly translates into increased demand for energy, water, transport and other natural resources. This phenomenon is accompanied by a growing level of consumption, which leads to an increase in pollutant emissions, environmental degradation and an increase in social and infrastructural problems (European Environment Agency, 2020). In particular, this applies to phenomena such as air pollution, traffic noise, limited access to green spaces, as well as the growing costs and difficulties associated with the management of municipal waste and wastewater. At the same time, many cities are struggling with ageing infrastructure, the modernisation of which faces numerous technical, legal and financial barriers inherent in public funds management systems. The housing deficit, public transport congestion and the increasing burden on energy systems also remain significant problems (Ministerstwo Funduszy i Polityki Regionalnej, 2021; Instytut Rozwoju Miast i Regionów, 2022) Today, cities act as key nodes of concentration of financial, population and cultural flows, becoming the main centers for generating economic growth. In the conditions of dynamic and inevitable technological, social and economic changes, it is precisely those centers that are able to effectively implement innovations that gain an advantage in attracting human capital, creating new jobs and shaping sustainable and competitive urban communities.

In this context, eco-innovations – defined as any type of technological, organisational or social innovation that contributes to the improvement of the state of the natural environment and increasing the efficiency of resource use (Organisation for Economic Co-operation and Development, 2011) – are of particular importance. Their role in the transformation of cities is fundamental – they support the transition towards low-carbon, resource-efficient and future-proof systems. The aim of eco-innovation is not only to reduce energy consumption and consumption of raw materials, but also to reduce the emission of harmful substances, improve the quality of life of residents and stimulate economic development in accordance with the principles of sustainable development (United Nations Environment Programme, 2011).

According to data from the Central Statistical Office, in June 2023, 22.4 million people lived in Polish cities, which accounted for 60% of the country's total population. The scale of urbanization will increase steadily in the coming decades – forecasts indicate that by 2050 two-thirds of the world's population will live in cities. A high concentration of population means not only economic potential, but also enormous pressure on the environment, resulting from, among m.in example, pollutant emissions, excessive energy consumption and limited availability of natural resources. For this reason, cities are becoming spaces with special potential – but also responsibility – in the field of implementing innovative environmental solutions.

Eco-innovations, as innovative technologies, organizational models and social practices, support the reduction of the negative impact of human activity on the environment, improve the efficiency of resource management and increase the quality of life of residents (Szymańska, 2016). The literature on the subject emphasizes that eco-innovation is not only an element of sustainable development, but also a factor increasing the competitiveness of cities. Motivations for the implementation of eco-innovations result not only from legal regulations and cost pressures, but also from a wide set of supply conditions, such as the availability of technological resources, organizational specificity of entities, innovations in management, conditions of competition and consumer expectations (Horbach, 2008).

Urban transformation based on eco-innovation requires not only the right technologies, but also friendly institutional, legal and financial conditions. In recent years, a number of instruments have been implemented at both EU and national level to support this process. These include, m.in example, green public procurement (GPP), environmental technology verification systems (ETVs) or environmental certificates such as Blue Angel, EU Ecolabel or Nordic Swan (European Commission, 2021; European Commission – Joint Research Centre, 2018; Umweltbundesamt, 2021).

Despite the availability of these tools, the level of implementation of eco-innovations in organizational units of Polish cities remains low. Research points to a number of barriers: lack of competence and knowledge among decision-makers, complicated administrative procedures and difficulties in obtaining funding (Instytut Ochrony Środowiska – Państwowy Instytut Badawczy, 2020). This shows that it is crucial not only to develop technology, but also to strengthen institutional trust, build environmental awareness and create a stable political and financial framework.

In the face of the intensifying climate crisis and the growing importance of cities as centres of socio-economic transformation, it is necessary to develop effective strategies to enable their sustainable development. Poland, as a country that is intensively urbanizing, is facing the challenge of rapid urban transformation in line with the assumptions of the European Green Deal. There is an urgent need to identify specific barriers and drivers for the implementation of eco-innovations that can act as a catalyst for this transformation. The article responds to the

current demand of policymakers, scientists and practitioners for knowledge that supports the development of climate-neutral urban policies.

The research problem posed by the authors concerns the answer to the question: *What institutional, financial and social factors have the greatest impact on the effectiveness of the implementation of eco-innovations in Polish cities?* In the study, the authors attempted to show that the integration of institutional instruments, appropriate financial mechanisms and activities to increase social awareness contributes to a significant acceleration of the implementation of eco-innovations in urban units in Poland. The authors are of the opinion that the identification and analysis of key institutional, financial and social factors allows for a better understanding of the conditions in which Polish cities function. This makes it possible to develop more effective strategies for implementing eco-innovations that will be adapted to local realities. A clear identification of barriers and opportunities fosters sound investment and organisational decisions, as well as the creation of a stable policy framework to support the green transition. As a result, such identification can significantly accelerate the pace of implementation of eco-innovative solutions and increase their effectiveness in practice.

The originality of this paper lies in its interdisciplinary approach, combining perspectives from urban management, architecture, and data analysis to explain the mechanisms that determine the effectiveness of eco-innovation in Polish cities. Unlike previous studies that focused mainly on the technological or environmental dimensions, this research integrates institutional, financial, and social aspects, providing an empirical framework for understanding governance-based eco-innovation as a new model of urban sustainability in Central Europe. The paper contributes to the literature by linking national policy instruments with local implementation practices, offering insights relevant to both academic research and urban policy.

To sum up, the main objective of this article is to analyze institutional, financial and social factors influencing the implementation of eco-innovations in Polish cities. The authors review the literature and national and EU strategic documents, identifying existing barriers and good practices. The article provides recommendations for local governments, decision-makers and urban practitioners that can support the process of green transition towards sustainable, low-carbon urban development.

2. Methods

The research presented in this article was conducted based on the method of triangulation of sources, which consists in combining the analysis of scientific literature, strategic documents and case studies of the implementation of eco-innovations in Polish and European cities. The use of this method allowed for more comprehensive and reliable results by collating data

from different sources and perspectives. The literature analysis included publications in the field of:

- theory of sustainable development,
- Smart Cities *concept*,
- green transition,
- adaptation of cities to climate change,
- and environmental and eco-innovation.

The criteria for selecting sources were: scientific value (indexed journals, recognized authors), topicality (mainly publications from the last 10 years), and a direct thematic connection with the issues of urban policy, technology implementation and design aimed at the needs of residents.

In addition, as part of the work presented in the article, the:

- national and EU strategic policies (including m.in. the European Green Deal, the National Urban Policy 2030, the Responsible Development Strategy),
- reports and expert opinions of public institutions and international organizations (e.g. European Commission, OECD, UN-Habitat),
- legal acts on waste management, energy efficiency and green public procurement in Poland.

The third phase of the research was the analysis of selected case studies, in particular those using *living labs* to test innovative environmental solutions and disseminate new technologies. These included:

- eco-innovation projects implemented in Polish cities: Warszawa, Krakow, Łódź, Wrocław, Rzeszów and Gliwice,
- selected foreign examples.

The criteria for selecting cases were: belonging to the space of Polish or European cities, the variety of implementation instruments used (e.g. technological, organizational, legislative) and the diverse scale of action (from pilot projects to urban projects of a systemic nature).

At the last stage, a comparative analysis was carried out, which included:

- a review of good practices in the implementation of eco-innovations in Europe, including particular emphasis on the activities undertaken by Polish cities,
- identification of the main barriers and factors conducive to the implementation of eco-innovation in the urban context,
- assessing the potential of institutional and technological tools that can support the sustainable transformation of cities.

The aim of such a selected and applied methodology was not only to map existing practices, but also to identify patterns and conditions for the effective implementation of eco-innovations that can be replicated in other cities in Poland. The next steps of the presented methodology allow for:

- reducing interpretation errors and increasing the reliability of conclusions,
- deep understanding of the implementation context and the specifics of local conditions,
- understanding the basis for assessing the consistency of the strategy with real actions.

The analysed data covered the period from 2015 to 2024, which allowed to capture both the beginnings and the effects of the implementation of the latest instruments supporting eco-innovation.

3. Literature review

3.1. Definitions of eco-innovation (EU, OECD, National)

The concept *of eco-innovation* does not have a single, universally binding definition, which results from the interdisciplinary nature of this phenomenon and its dynamic development in various sectors of the economy and public policy. In the literature on the subject and strategic documents, there are a number of definitional approaches that take into account various aspects of eco-innovation – from technological to organizational and social.

One of the most frequently cited definitions comes from a report by the European Commission (2007), which defines eco-innovation as: *all forms of innovation that lead to significant and observable progress in achieving environmental objectives by reducing environmental impact or using natural resources more efficiently* (Eco-Innovation Action Plan, 2007).

A similar approach is proposed by the OECD, which defines eco-innovation as *the process of developing new products and services that contribute to sustainable development by reducing the negative environmental impacts of economic activity* (OECD, 2009).

In Polish strategic documents, such as the "National Smart Specialization" (KIS), eco-innovations are understood as activities that lead to the development and implementation of new or significantly improved products, processes, services and business models aimed at reducing pressure on the environment and promoting sustainable development.

In turn, the scientific literature indicates that eco-innovations include not only the technological aspect (e.g. energy-efficient devices), but also:

- organisational innovations (e.g. new models of management in waste management),
- social (e.g. changes in consumer lifestyles),
- systemic (e.g. transformations in spatial planning and urban mobility).

Horbach (2008) emphasizes that eco-innovation can be motivated by both external factors (legal regulations, social pressure) and internal factors (the need to reduce costs, increase efficiency, competitive advantage). Thus, eco-innovation is the result of synergy between technological possibilities, institutional conditions and changing social expectations. Selected

definitions of eco-innovation together with an analysis of the key elements of a given approach are shown in Tab. 1.

Definitions of eco-innovation differ by emphasis on technological, institutional, or social dimensions. Table 1 summarizes the most common definitions proposed by key international organizations.

Table 1.
Comparison of eco-innovation definitions

Source	Key elements
European Commission (2007)	Innovation reducing environmental impact and improving resource efficiency.
OECD (2009)	New products and services contributing to sustainable development.
National Environmental Policy 2030 (Poland)	Environmental technologies adding value throughout the product life cycle.
Fussler, James (1996)	Market value creation combined with reduced environmental footprint.

Source: own study.

To conclude the review, eco-innovation should be understood as an inherently interdisciplinary construct encompassing technological, organisational, social, and institutional change. There is broad agreement that its core purpose is to reduce environmental impacts and improve resource efficiency. The main differences between definitions lie in scope and emphasis—whether prioritising technology-driven advances, systemic transformations, or societal change. Policy documents adopt a pragmatic stance, whereas scholarly work aims for conceptual precision and completeness. Overall, eco-innovation emerges as a multidimensional, evolving framework that connects policy and scholarship and guides practice toward verifiable environmental improvements.

3.2. Typology of eco-innovation

Eco-innovation represents a crucial dimension of sustainable development, aiming to mitigate the negative environmental effects of urbanisation and promote more efficient resource use. In Europe, its development has been strongly driven by the transformation processes linked to the **European Green Deal** (EC, 2019) and related policy challenges such as climate-change adaptation, energy decarbonisation, circular-economy business models, and the introduction of zero-emission and waste-free production systems.

Eco-innovations can be classified according to different criteria and analytical perspectives, indicating that their emergence depends on the interaction between technology, public policy, and market dynamics (Rennings, 2000; Horbach et al., 2012; Hojnik, Ruzzier, 2016). Table 2 presents a condensed typology commonly used in urban sustainability research.

Table 2.
Typology of eco-innovation

Type of eco-innovation	Main Focus and examples
Technological	New or improved products and processes reducing emissions and resource use (e.g., renewable energy, energy-efficient lighting, wastewater treatment).
Organisational	Management and logistics models improving environmental performance (e.g., ISO 14001, sustainable supply chains).
Social	Behavioural and community innovations promoting sustainable practices (e.g., sharing economy, city bikes, community gardens).
Policy-driven	Innovations introduced through regulation or incentives (e.g., green public procurement, emission standards).

Source: own elaboration based on Rennings (2000), Horbach et al. (2012), and Hojnik, Ruzzier (2016).

Rennings (2000) proposed a further distinction between *innovations by effect*—those that generate positive environmental outcomes indirectly—and *innovations with intent*, explicitly designed for environmental improvement. This approach helps distinguish between solutions consciously aimed at improving the quality of the environment and those that produce ecological benefits as secondary effects. Such differentiation is especially relevant for urban management, where both deliberate environmental strategies and incidental benefits can support sustainable development.

The sources of eco-innovation are generally divided into *technology push*, *regulatory pull*, and *market pull* mechanisms (Rennings, 2000). Technology push stems from advances in science and industry, regulatory pull arises from legal and policy frameworks, and market pull reflects consumer and competitive pressures. Empirical studies indicate that the diffusion of eco-innovation depends on the interplay among these factors, supported by environmental standards, certification systems, and fiscal incentives (Chaudhuri, Mukhopadhyay, 2013).

The typology of eco-innovation highlights the interdependence of technological, organisational, social, and policy dimensions. Understanding these relationships allows policymakers and urban practitioners to identify effective mechanisms that foster the green transformation of cities and to integrate innovation processes into comprehensive sustainable-development strategies.

3.3. Urban Eco-Innovations

Cities, as the main centers of resource consumption and pollutant emissions, are key arenas for testing and implementing eco-innovations. Within the urban context, these innovations aim to improve air quality, reduce CO_2 emissions, increase the energy efficiency of buildings and infrastructure, and strengthen systems for water and waste management. They also promote sustainable mobility, climate adaptation through green and blue infrastructure, and civic participation in environmental education (United Nations Human Settlements Programme, 2020).

For the purposes of this study, **urban eco-innovation** is defined as new or improved products, services, processes, or technologies implemented in cities that effectively reduce the negative environmental impact of urban activities, enhance resource efficiency, and improve residents' quality of life. Their distinguishing feature lies in their ability to generate both ecological and socio-institutional value by integrating technological solutions into planning, infrastructure, and decision-making processes. Local governments—through public procurement, spatial planning, transport, education, and municipal management—play a decisive role in creating a favorable regulatory, financial, and organizational framework (European Commission, 2019).

Cities can act as 'urban living labs', where innovative solutions are tested in real-world conditions, with the active participation of citizens and stakeholders. These are spaces where environmental innovations are tested in real urban conditions, with the active participation of residents, local governments, the private sector, science and non-governmental organizations. Urban Living labs combine scientific research with urban practice, allowing you to quickly test the effectiveness of new solutions through micro-scale experimentation before the solutions are implemented at the city-wide level. It is very important that this way of introducing innovations promotes social participation. Residents are not only recipients of innovations, but also co-creators.

Examples of leading European urban living labs are presented in **Table 3**, showing different approaches to integrating eco-innovation into sustainable city management.

Table 3.
Typology of eco-innovation

City / Initiative	Main focus areas	Key outcomes / lessons
Amsterdam – Amsterdam Smart City	*Energy efficiency in buildings, electric mobility, shared transport, smart street lighting*	Integration of digital technologies and citizen participation in sustainable urban management
Copenhagen – Climate Neutral Strategy	Green and blue infrastructure, innovative bicycle transport, air-quality monitoring	Climate adaptation and data-driven management of urban systems
Vienna – Smarter Together (Horizon 2020)	*Energy-efficient housing retrofits, electromobility, creation of social spaces*	Collaborative innovation through EU-funded pilot projects and social inclusion

Source: own elaboration based on Amsterdam Smart City (2020), City of Copenhagen (2021), and Smarter Together Vienna (2020).

These examples demonstrate that urban living labs accelerate the testing and implementation of eco-innovations, strengthen interdisciplinary cooperation, and increase public acceptance of environmental projects. They also reveal the importance of linking technological, social, and institutional innovation in urban-development strategies, creating a foundation for the long-term transition toward climate-neutral cities.

As shown in Figure 1, the main determinants of urban eco-innovation include technological factors, social demand, regulatory frameworks, and urban strategies.

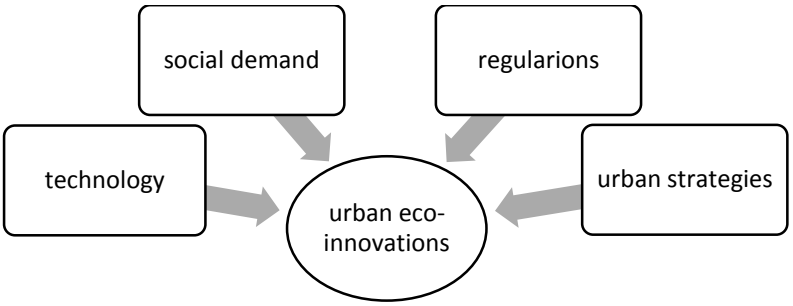

Figure 1. Determinants of urban eco-innovation.

Source: own elaboration based on Horbach, Rammer, Rennings (2012).

According to the literature, the main determinants of eco-innovation are technology, market forces, regulations, and company strategies (Horbach, Rammer, Rennings, 2012). In the urban context, these factors can be translated into:

- technologies that include modern infrastructure and digital systems such as smart energy grids, air-quality sensors, sustainable public transport, waste management systems, and energy-efficient construction;
- social demand arising from residents' expectations for sustainable services and public spaces;
- regulations concerning environmental protection, building standards, low-emission zones, and financial incentives;
- urban strategies defining development visions, cooperation programmes, and strategic goals (e.g., *smart city*, *resilient city*). Together, these components create the institutional and market framework for eco-innovation and determine its pace and scale.

Social and institutional capital are key factors in the generation and implementation of eco-innovations. They reflect the ability to build cooperation, trust, and partnership among urban actors. High social capital strengthens innovation processes through coordination, knowledge exchange, and resource mobilisation. Residents play a major role as co-creators of innovation: their attitudes and behaviours stimulate demand for eco-friendly solutions such as community gardens, zero-waste initiatives, and participation in public consultations. Shared services like car-sharing or city bikes also foster environmental awareness. Analyses of urban case studies confirm that citizen engagement increases both the acceptance and sustainability of implemented projects.

Non-governmental organisations and public institutions have a crucial role in implementing eco-innovations. NGOs, acting as intermediaries between communities and city authorities, mobilise residents for environmental activities and education. Municipal governments coordinate and regulate implementation processes, providing legal, financial, and organisational frameworks. Promoting cross-sectoral cooperation through participatory tools—such as citizens' budgets, sustainability councils, and civic panels—helps scale successful pilot projects into strategic programmes, fostering the *diffusion of innovation*.

The greatest effects are achieved when residents, NGOs, and public institutions cooperate. Such collaboration combines expert and local knowledge, enables better adaptation of solutions to social needs, and ensures legitimacy and social acceptance of innovation. Examples include local energy plans (*Amsterdam Energy Transition*), participatory spatial planning with citizens' panels in Vienna, and Warsaw's citizens' budget supporting ecological micro-innovations like green stops and community gardens.

The success of eco-innovation also depends on the cultural dimension, which shapes social acceptance and readiness to use new solutions. Environmental education and cooperation with research centres play a crucial role. High environmental awareness fosters faster adaptation of shared transport, waste segregation, and circular-economy systems. Scandinavian countries exemplify this approach, where a culture of simplicity, thrift, and closeness to nature encourages public support for innovation. Similarly, Japan's tradition of recycling and reusing resources facilitates the implementation of circular-economy practices.

A decisive factor for effective eco-innovation is **financial management**, ensuring access to capital and reducing investment risk. Proper financial instruments enable infrastructure projects, experimentation, and technology scaling. Across Europe and Poland, the EU's Structural and Investment Funds, the Cohesion Fund, Horizon Europe, and LIFE Programme support energy efficiency, circular economy, and low-emission mobility. At the national level, the *National Fund for Environmental Protection and Water Management (NFEP&GW)* and regional funds co-finance local projects. Other instruments include *green bonds*—used by cities such as Paris and Gothenburg to finance public transport modernisation and green infrastructure—and *public-private partnerships (PPPs)* that share costs and risks while accelerating innovation.

Table 4.
Financial instruments supporting urban eco-innovation

Instrument/Mechanizm	Main purpose and examples	Key benefits
EU Structural and Investment Funds (Cohesion Fund, Horizon Europe, LIFE)	Financing projects in energy efficiency, circular economy, and low-emission mobility across EU member states.	Long-term, stable funding; supports large-scale infrastructure and research projects.
National and regional funds (*NFEP&GW*, regional environmental funds)	Co-financing local-government initiatives such as renewable energy, waste-management systems, and sustainable transport.	Facilitates municipal participation; complements EU programmes.
Green bonds (e.g., Paris, Gothenburg))	Bonds issued by cities to fund pro-environmental projects such as public-transport modernisation or green infrastructure	Attracts private investors; promotes transparency and accountability.
Public-private partnerships (PPPs)	Shared investments in renewable energy, energy-efficient buildings, or water and sewage systems.	Distributes risks and costs; accelerates implementation of innovative solutions.

Source: own elaboration based on European Commission (2023), NFEP&GW (2024).

These instruments together create a diversified and complementary funding ecosystem. By combining EU, national, and local sources with private-sector participation, cities can accelerate innovation, lower financial risk, and enhance long-term sustainability.

Urban eco-innovation integrates technological, institutional, financial, and social dimensions of sustainability. Its success depends not only on advanced technologies but also on civic participation, effective governance, cultural readiness, and well-designed financial frameworks. Understanding these interconnections enables policymakers to design adaptive, inclusive, and resilient strategies for sustainable urban transformation.

4. Examples of good practices for implementing eco-innovations in Polish cities

4.1. Building urban competences

In Poland, a significant shift in large-city management priorities is visible — from traditional infrastructural approaches to strategies focused on adaptive capacity, environmental awareness, and inclusiveness. In 2022, ten Polish cities joined the EU Mission: Climate-Neutral and Smart Cities, aiming to achieve climate neutrality. By 2023, five of them — Warszawa, Kraków, Łódź, Wrocław, and Rzeszów — received the EU Cities Mission Label after expert evaluation. In 2024, these cities gained access to the Capital Hub platform, which offers technical, financial, and advisory support for climate adaptation projects.

Building urban competences in eco-innovation management is one of the main conditions for successful implementation. Cities must strengthen technical and organisational skills, develop cross-sectoral cooperation capacities, and improve social communication and environmental education. Competence development should include strategic planning, fundraising, project management, and monitoring technological innovations. Recommended activities involve training programmes for public officials, partnerships with universities and research institutes, establishing *urban living labs*, and creating platforms for knowledge exchange and pilot projects testing innovative solutions.

Strengthening administrative and social competences enhances the adaptive capacity of cities, enabling effective collaboration between residents, academia, business, and public institutions — a prerequisite for sustainable transformation.

4.1.1. Warszawa

Warszawa actively implements eco-innovations aimed at climate adaptation and improving residents' quality of life. Its actions combine infrastructural investments and community programmes. The city greens public spaces, revitalises water reservoirs, and greens tram tracks to enhance air quality and increase rainwater retention. These initiatives support flood protection and sustainable water management.

As shown in Figure 2, the *Czajka Wastewater Treatment Plant* represents a key eco-innovation in energy-efficient water processing.

Figure 2. Czajka Wastewater Treatment Plant in Warsaw - an example of eco-innovation.

Source: Wodociągi Warszawskie. (2025, September 21). *Zakład "Czajka"*. Retrieved September 21, 2025, from https://www.mpwik.com.pl/view/zaklad-czajka

Warszawa involves residents in eco-innovation through subsidy programmes for local environmental projects and the publication of the *Warsaw Environmental Decision* guide promoting green building and low-emission standards. Selected districts, such as Praga Południe and Ursynów, operate as *urban living labs*, where advanced environmental technologies are tested before wider implementation.

Warszawa integrates technological, social, and spatial eco-innovations, using pilot districts as testing grounds for scalable environmental solutions.

4.1.2. Kraków

Kraków participates in the EU NetZeroCities initiative and focuses on reducing greenhouse gas emissions, particularly in the building sector. The *NEEST Project* aims to improve energy efficiency through large-scale retrofitting of 1970s residential blocks (see Figure 3).

Kraków collaborates with the National Centre for Research and Development (NCBR), Energy Forum, and National Centre for Nuclear Research (NCBJ) to integrate scientific knowledge with practical experience. This cooperation has led to the creation of a digital tool supporting deep thermal modernisation planning for residential and public buildings. Eco- innovations implemented in Kraków include advanced construction technologies, green investment models, revitalisation of urban spaces, and citizen engagement in the energy transition.

Kraków demonstrates how institutional partnerships and digital tools enhance the efficiency of eco-innovation implementation, particularly in climate-oriented projects.

Figure 3. NEEST project - modernization of blocks from the 70s - an example of eco-innovation.

Source: Wodociągi Warszawskie. (2025, September 21). *Zakład "Czajka"*. Retrieved September 21, 2025, from https://www.mpwik.com.pl/view/zaklad-czajka

4.1.3. Łódź

Łódź addresses environmental degradation and high energy consumption while capitalising on its industrial heritage and research potential. Its priorities include expanding green areas, improving water retention, and adapting to climate change through green–blue infrastructure that cools urban areas and reduces flooding.

As shown in **Figure 4**, projects such as the greening of tram tracks illustrate this strategy.

Figure 4. Greening of tram in Łódź.

Source: Sztuka Krajobrazu. (2025, September 21). *Zielona rewolucja w Łodzi w 2025 r.* Retrieved September 21, 2025, from https://sztuka-krajobrazu.pl/5750/artykul/zielona-rewolucja-w-lodzi-w-2025-r

The city modernises residential and public buildings, integrating renewable energy technologies such as photovoltaic systems and heat pumps. It also invests in low-emission public transport, cycling infrastructure, and shared mobility. Digital innovations include smart lighting, air-quality monitoring, and platforms supporting urban planning and citizen communication. *Urban Living Labs* enable cooperation between residents, universities, and private companies.

Łódź combines adaptive infrastructure with digital tools and participatory mechanisms, creating an integrated model of sustainable urban governance.

4.1.4. Wrocław

Wrocław, one of Poland's largest urban centres, faces the challenge of balancing dynamic development with environmental protection. The city has long invested in **green–blue infrastructure** to counteract heat waves and flooding, including the construction of rainwater retention systems, new reservoirs, and riverbank revitalisation. Urban greenery—parks, rain gardens, and green stops—plays a key role in improving air quality and comfort.

Figure 5 presents an example of visible architectural greening supporting Wrocław's green city vision.

Figure 5. The green façade of the Municipal Office building at Świdnicka Street.

Source: Wroclaw.pl. (n.d.). *Zielona Stolica Europy – Wrocław na zielono.* Retrieved from https://www.wroclaw.pl/zielony-wroclaw/wroclaw-zielona-stolica-europy-parki-kieszonkowe-zielone-sciany-parklety-woonerfy

Wrocław also modernises public buildings through energy retrofits and PV installations, supports prosumer energy, and develops low-emission transport. Smart-city tools (air-quality monitoring, traffic optimisation, and smart lighting) are integrated with *Urban Living Labs*, where residents and universities test solutions in real conditions.

Wrocław links infrastructure renewal with social innovation and digital transformation, illustrating a holistic model of climate-neutral urban development.

4.1.5. Rzeszów

Rzeszów, one of five Polish cities with the **EU Cities Mission Label (2023)**, invests in renewable energy and smart technologies. The city promotes photovoltaic systems on public buildings, heat pumps, and energy storage, supporting prosumer investments through subsidies and partnerships.

Figure 6 illustrates one of Rzeszów's flagship smart-city projects.

Figure 6. Smart waste bins.

Source: MZBM Rzeszów. (n.d.). *Rzeszów testuje inteligentne pojemniki na odpady – innowacja na terenie zarządzanym przez MZBM Rzeszów.* Retrieved from https://mzbm.rzeszow.pl/rzeszow-testuje-inteligentne-pojemniki-na-odpady-innowacja-na-terenie-zarzadzanym-przez-mzbm-rzeszow/

4.1.6. Gliwice

Gliwice, a leading city in the Upper Silesia–Zagłębie Metropolis, integrates innovation with academic collaboration. Many eco-innovations result from cooperation with the Silesian University of Technology, enabling the development of advanced green technologies.

The upcoming *Green Energy Park*—a combined heat and power facility—will generate energy from residual municipal waste starting in 2028. The city also piloted the BB-1 autonomous electric minibus project (Figure 8.) developed jointly with the Silesian University of Technology and the University of Silesia. The prototype, tested in 2023 under the *Urban Living Lab* model, carried over 3000 passengers and received positive public feedback.

Figure 7. Green Energy Park.

Source: gov.pl. (n.d.). *Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej – NFOŚiGW przeznaczy ponad 270 mln zł na Park Zielonej Energii w Gliwicach.* Retrieved from https://www.gov.pl/web/nfosigw/nfosigw-przeznaczy-ponad-270-mln-zl-na-park-zielonej-energii-w-gliwicach

Gliwice continues to expand e-mobility, traffic-management systems, and urban greening, counteracting heat islands and improving public-space aesthetics. Collaboration between academia, the city, and private industry supports the diffusion of eco-innovation and the development of smart solutions in energy, transport, and planning.

Figure 8. BB-1 Autonomous Electric Minibus.

Source: Dzisiaj w Gliwicach. *https://dzisiajwgliwicach.pl/przyszlosc-jest-tu-i-teraz-stworzony-w-gliwicach-minibus-rusza-w-droge-bez-kierowcy/?cn-reloaded=1*

Gliwice exemplifies successful science–city partnerships that turn innovation into practical, resident-oriented eco-solutions.

4.2. Eco-innovations in cities – sector analysis

The examples of Polish analysed above show that contemporary urban policy increasingly integrates technological innovation with social participation and sustainable spatial development. Eco-innovation is no longer viewed merely as a set of technological projects but as a systemic process that transforms the way cities function, manage resources, and engage residents. This evolution responds to the rapidly changing expectations of urban communities, shaped by digitalisation, climate awareness, and new models of participatory governance.

Urban eco-innovation reflects a multidimensional transformation linking environmental performance, technological progress, and social well-being. The main directions of this transformation include the implementation of green and blue infrastructure improving microclimate and biodiversity (Warszawa, Łódź, Wrocław), energy-efficient construction and retrofits contributing to urban decarbonisation (Kraków's NEEST project), and integration of technology in public space through solar benches, environmental sensors, and other smart solutions (Warszawa, Rzeszów). The spread of IoT-based systems enables dynamic management of energy, transport, and waste (Gliwice, Rzeszów), while augmented reality (AR) increasingly supports environmental education and civic engagement.

According to the literature, cities can be analysed by their dominant economic sectors—agriculture, industry, and services—each defining a distinct pathway of sustainable transformation.

- **Agro-technological cities**, such as *Almería (Spain)*, combine precision agriculture with renewable energy and technological services. Although agriculture plays a minor role in large Polish cities, its principles inform peri-urban planning and local food resilience strategies.

- **Industrial cities**, including *Łódź* and *Gliwice*, use eco-innovation to revitalise degraded post-industrial areas, transforming them into mixed-use districts focused on education, culture, and circular production. This mirrors European trends linking industrial regeneration with the circular economy.
- **Service-oriented cities**, such as *Warszawa*, *Kraków*, and *Wrocław*, prioritise digitalisation, smart mobility, and citizen-centred innovations, demonstrating how eco-innovation can serve as a governance tool that improves quality of life and environmental resilience.

European experiences complement these patterns. *Bergen (Norway)* integrates landscape and climate neutrality in spatial policy, while *Almería (Spain)* represents the synergy between agriculture, technology, and sustainability. Together, they show that effective eco-innovation depends on aligning environmental goals with local economic and institutional contexts.

A summary of the sector analysis is provided in Table 5.

Table 5.
Selected typologies of eco-innovation

Urban area	Physical Elements/ Infrastructure	Digital/ Smart Elements	Design Notes
Transport and mobility	Hybrid Electric Vehicles, EV Charging Stations, City Bike & Bike Stations, Smart Stops/Shelters, Parking Lots with EV Spaces	Traffic Control Systems, Car-Sharing / Bicycle Mobile Apps, Traffic Monitoring	Places for chargers, bicycle stops and stations, space for EV parking lots, integration with the Smart City system should be provided
Energy and buildings	Passive/Energy Efficient Buildings, Photovoltaic Panels, Solar Benches & Solar Lighting, Smart LED Street Lights	Energy Management Systems (EMS), Energy Consumption Monitoring and Network Load Optimization	Plan PV panel spaces, grid access, and easy equipment maintenance
Water and water and sewage management	Retention Reservoirs & Ponds, Green Area Irrigation Systems, Water Treatment Plants	Water Quality Monitoring, Irrigation Control Systems, Weather Data and Water Consumption Analysis	Provide land reserves for reservoirs and rainwater, integration with the Smart City system for optimization
Greenery and public space	Community gardens, green roofs and walls, Benches and pergolas with solar function, Eco-friendly playgrounds	Soil moisture and planting monitoring systems, Intelligent management of public space	Provide space for solar benches and gardens, integration with other systems (energy, water)
Infrastruktura IT / Smart City	Wi-Fi Points, Smart Air, Noise, Motion Sensors, Telemetry Stations & Local Servers	Urban Data Integration (IoT) Systems, Analytics & Prediction Platforms, Citizen Applications	Necessary network infrastructure, space for sensors and nodes, compatibility with other urban systems
Education and environmental awareness	Information boards in public spaces, Interactive ecopoints in parks and schools	Educational mobile apps, Energy/water monitoring platforms for residents	Placement of points in accessible locations, integration with educational programs
Health and quality of life	Urban greenery, recreational areas, Air filters in sensitive places, Bicycle and pedestrian paths	Air quality monitoring, Smog or excessive noise warning systems	Design with accessibility and security in mind, integration with Smart City systems

Source: own elaboration based on municipal and European smart-city strategies (2019-2025).

5. Factors conducive to the implementation of eco-innovations in cities in Poland

Building upon the preceding discussion on good practices and the development of urban competences that facilitate eco-innovation, this section explores the broader set of factors that enable their effective implementation in Polish cities. It aims to identify and analyse the institutional, social, economic, and environmental determinants that create favourable conditions for the diffusion of eco-innovative solutions. By examining these interrelated dimensions, the section provides a deeper understanding of the systemic foundations that underpin the successful transformation of Polish cities towards sustainability.

5.1. Institutional and legal instruments

5.1.1. National and EU regulations supporting sustainable development

Legal frameworks at both EU and national levels form the foundation for implementing sustainable development policies and creating conditions for eco-innovation. The European Green Deal (2019) establishes a roadmap toward climate neutrality by 2050, operationalised through instruments such as the Fit for 55 package, the EU Taxonomy, and sectoral directives on energy efficiency (2012/27/EU), renewable energy (RED II, RED III), and the circular economy. These are reinforced by financial mechanisms such as the Just Transition Fund and Horizon Europe, which stimulate innovation and environmental protection.

In Poland, the Environmental Policy of the State 2030 defines national priorities, linking environmental goals with socio-economic development. It is complemented by key sectoral acts, including the *Environmental Protection Law* (2001), the *National Energy and Climate Plan 2021-2030*, the *Renewable Energy Sources Act* (2015), and the *Circular Economy Strategy 2030*. Together, these documents form a coherent policy framework promoting energy efficiency, resource management, and biodiversity conservation.

However, their practical impact is constrained by uneven enforcement and weak coordination between national, regional, and municipal levels. Although Polish legislation aligns with EU objectives, implementation delays and limited administrative capacity often reduce the effectiveness of these frameworks at the city level.

5.1.2. Green Public Procurement Policy

Green Public Procurement (GPP) is one of the most effective instruments for stimulating eco-innovation through market demand. As the public sector accounts for nearly 14% of EU GDP (European Commission, 2016), local governments can significantly influence innovation pathways by integrating environmental criteria into tenders.

Polish cities have begun applying GPP in transport, construction, and waste management — for instance, purchasing electric buses, LED street lighting, or certified sustainable buildings (BREEAM, LEED). However, despite the strong regulatory base, adoption remains fragmented

and inconsistent. Barriers include low awareness among procurement officers, lack of training, fear of litigation when using restrictive criteria, and limited availability of certified products.

GPP's potential to drive innovation is thus underutilised: it remains more a policy ambition than a systemic practice. A stronger institutional culture, clearer national guidelines, and incentives for municipalities are necessary to unlock its transformative potential.

5.2. Technology certification and verification mechanisms

5.2.1. Environmental Technology Verification (ETV)

Environmental Technology Verification (ETV), established under ISO 14034, serves as a vital mechanism for building credibility and trust in eco-innovation. It provides independent verification of manufacturers' claims regarding technological performance, confirming their validity under real operating conditions. Unlike traditional certification systems based on uniform criteria, ETV enables the selection of verification parameters suited to innovative solutions that often exceed regulatory standards or fall outside conventional assessment methods. Introduced by the European Commission in 2012 within the Eco-Innovation Action Plan (EcoAP), the programme significantly supported the market entry of new environmental technologies and reduced investment uncertainty, particularly for small and medium-sized enterprises.

Although the EU-level initiative concluded in 2022, the ETV framework continues to operate through internationally harmonized standards. The ISO 14034: *Environmental Management – Verification of Environmental Technologies* standard, adopted in Europe in 2019, ensures methodological consistency, transparency, and reliability of results. Accredited Verification Bodies (ISO 17020) and laboratories (ISO 17025) safeguard quality and impartiality, while verification statements issued by independent entities confirm both the technological and environmental performance of innovations. This, in turn, strengthens market confidence, lowers investment risk, and promotes wider adoption of eco-innovative solutions across urban and industrial contexts.

5.2.2. Environmental Certifications

Eco-labelling and certification systems such as the *EU Ecolabel*, *Blue Angel*, and *Nordic Swan* play a dual role as both market mechanisms and regulatory tools. They encourage producers to adopt environmentally friendly technologies and help consumers and public institutions make informed choices.

In urban contexts, certifications are widely used in GPP procedures — for example, as selection criteria for sustainable construction materials or energy-efficient equipment. Beyond procurement, certification schemes raise awareness among residents and promote a culture of sustainability and innovation. However, their voluntary character and lack of enforcement mechanisms reduce their systemic impact.

To increase their effectiveness, certifications should be more closely tied to fiscal incentives, funding criteria, and urban management standards, turning them from symbolic recognitions into practical drivers of transformation.

5.3. Financial support and grant programs

5.3.1. EU and national funds supporting urban eco-innovation

The development of eco-innovations in the urban environment would not be possible without adequate financial resources, which enable both research on new technologies and their practical implementation in the urban space. In this context, EU and national funds are of particular importance, as they are a basic tool for supporting the transformation of cities towards sustainable development.

One of the most important sources of funding at the national level is the European Fund for Infrastructure, Climate and Environment (FEnIKS), which replaced the previous Infrastructure and Environment Programme (OPIiŚ). This programme supports investments aimed at improving energy efficiency, developing low-emission transport, protecting environmental resources and adapting to climate change. In the urban area, FEnIKS enables the financing of projects such as the modernization of heating networks, the development of renewable energy sources or the introduction of innovative solutions in waste management.

At the EU level, the LIFE Programme plays a key role, being the only financial instrument of the European Union entirely dedicated to environmental protection and climate action. This program supports demonstration and pilot projects that test new solutions in the field of natural resource protection, reduction of greenhouse gas emissions, improvement of air quality or resource efficiency. Climate change adaptation measures such as green-blue infrastructure, rainwater retention systems and low-emission public transport are particularly important for cities.

An equally important instrument is the Horizon Europe research and innovation programme (2021-2027), one of the pillars of which focuses on supporting research and innovation related to the European Green Deal. This program enables financing of projects related to the energy transition, digitization of urban infrastructure, implementation of intelligent transport management systems or the development of the circular economy.

It is worth noting that EU funds are often supplemented by national instruments, such as the support offered by the National Fund for Environmental Protection and Water Management (NFOŚiGW), which finances projects related to improving energy efficiency, the use of RES, air protection and modern waste management. Coordination of activities between the national and EU levels increases the capacity of cities to obtain funds for the implementation of innovative environmental projects.

Thanks to national and EU funds, it is possible not only to finance costly infrastructure investments, but also to support research, testing of new solutions and their dissemination in urban practice. As a result, these mechanisms are the basis for the implementation of sustainable

development policies and the effective implementation of the European Green Deal at the local level.

As a discussion and critical remarks one shpuld underline strong framework with gaps in enforcement. The legal and institutional frameworks at both EU and national levels provide a comprehensive foundation for the implementation of eco-innovations in Polish cities. Instruments like the European Green Deal, the Fit for 55 package, and Poland's Environmental Policy of the State 2030 present clear targets and strategic directions.

However, the effectiveness of these instruments is often undermined by implementation challenges. Despite the existence of progressive legal mechanisms, Poland has frequently been criticized for delays in adopting EU directives and inconsistent enforcement of environmental regulations. Additionally, the coordination between different levels of government (national–regional–local) can be fragmented, which reduces the practical impact of these policies on urban innovation.

Green Public Procurement (GPP) is presented as a powerful catalyst for eco-innovation. Its strategic importance is undeniable, especially considering the public sector's purchasing power. Yet in practice, Polish cities still struggle to systematically implement GPP policies. Barriers include:

- low awareness among procurement officers,
- insufficient training or guidance,
- fear of legal disputes when environmental criteria limit competition,
- limited availability of certified green products/services.

Thus, while the legal basis exists, GPP in Poland remains more of a policy ambition than a widespread practice.

Environmental Technology Verification (ETV) and eco-labels undoubtedly help increase transparency, reduce investment risk, and encourage consumer and institutional trust in green solutions. These mechanisms are especially important for SMEs developing new environmental technologies. However:

- the voluntary nature of these certifications reduces their penetration,
- lack of incentives or regulatory mandates to prioritize certified technologies weakens their market impact,
- the termination of the EU ETV pilot programme in 2022 may further reduce visibility and interest in verification systems unless a strong replacement is implemented.

EU and national funds such as FEnIKS, LIFE, Horizon Europe, and NFOŚiGW programmes represent robust financial foundations for urban eco-innovation in Poland. These programmes support both infrastructure modernisation and innovation development.

It shpuld be stressed that critical issues remain:

- administrative complexity and bureaucratic hurdles can discourage smaller municipalities,
- competition for funding is high, favouring larger, better-prepared cities,

- monitoring and evaluation mechanisms of funded projects are not always rigorous, leading to a gap between declared outcomes and real environmental impacts.

Eco-innovation in Polish cities is supported by a broad and well-developed system of instruments across regulatory, procurement, verification, and financial dimensions. However, a recurring pattern emerges: excellent strategic frameworks but uneven implementation.

Table 6.
Strengths and challenges of eco-innovation in Poland

Strengths	Challenges
• Alignment with EU green policy (Green Deal, Fit for 55, taxonomy). • Access to diversified financial support • Growing awareness of the role of public procurement and certification. • National strategies linking sustainability with economic development.	• Weak enforcement and regulatory compliance. • Low uptake and institutional resistance to GPP. • Limited penetration of technology verification tools. • Complex and competitive grant application procedures.

To effectively transition to a sustainable and innovative urban model, Polish cities must not only rely on existing instruments but also:

- strengthen local administrative capacity,
- increase institutional cooperation,
- simplify access to support programmes,
- promote mandatory or incentivised use of green criteria and certifications.

Without addressing these systemic issues, the implementation of eco-innovations risks remaining fragmented and insufficient, despite solid legal and financial foundations. It i salso very imortant that eco-innovation is not only about technologies but also about the systems, governance, and culture that enable them to thrive.

6. Barriers to eco-innovation in Polish cities

The implementation of eco-innovations in the urban environment is also associated with challenges, such as: fragmentation of competences, financial shortages, cultural barriers and social resistance to change. Therefore, an integrated and long-term approach that combines technological innovation with educational, institutional, and participatory activities is crucial (Instytut Rozwoju Miast i Regionów, 2022).

In view of increasingly strict EU environmental standards — particularly those stemming from the Europe 2030 Strategy — Poland must align its environmental performance with that of other Member States. This poses a significant challenge, as it requires catching up on decades of underinvestment in environmental protection (Piotrowska, 2012). According to the State of the Environment in Poland 2022 report, *Expenditures on environmental protection and water*

management remain at a very low level relative to GDP (Główny Inspektorat Ochrony Środowiska, 2022).

Since 2010, Poland has been among the countries with the lowest eco-innovation index in the Ecoinnovation Scoreboard, which contains a comparative assessment of European Union Member States in the field of research and innovation (European Commission, 2023). Compared to all countries, this result is significantly below the average. What is the main barrier, apart from the lack of public sector funding? *The Eco-Innovation Country Profile 2022 report* identifies key barriers to the introduction of eco-innovation in Poland.

From the consumer perspective, *greenwashing* remains a major issue, leading to distrust in environmentally friendly products and making it difficult to distinguish genuine innovation from marketing. Price sensitivity also limits the demand for ecological goods, while a lack of awareness of the circular economy concept slows the adoption of sustainable consumption patterns.

For enterprises, the main obstacles include late notification of legislative changes, ambiguities in legal provisions, and a lack of financial incentives to invest in innovation. Entrepreneurs point to complex and inconsistent regulations that complicate adaptation and increase uncertainty. Many companies also note that administrative procedures and overly restrictive interpretations of environmental law can discourage experimentation and innovation.

At the strategic level, the *Environmental Policy of the State 2030 – Development Strategy in the Area of Environment and Water Management* (Republic of Poland, 2019) identifies barriers such as low expenditure on R+D+I (Research, Development, Innovation), fragmented programmes with differing goals and operators, and a lack of measurable environmental indicators. The document also highlights the absence of a national database of environmental technologies, which could provide reliable information on available and emerging innovations. This information gap weakens coordination between research, industry, and public policy.

Despite eco-innovation being one of the most dynamically developing global markets — even surpassing ICT and pharmaceuticals in growth — the Polish capital market remains only moderately interested in financing environmental technologies (Republic of Poland, 2023). As noted by Burzyńska & Hajdys (2021), most companies engaged in eco-innovation concentrate on technological aspects, neglecting organisational changes, knowledge management, and human capital development — elements that are equally essential for sustainable innovation.

7. Disscussion

The findings presented in this paper confirm that the effective implementation of eco-innovations in Polish cities depends on the integration of institutional, financial, and social factors. This result is consistent with the conclusions of Horbach, Rammer and Rennings (2012), who emphasized the complementary role of regulatory push/pull and market demand in shaping environmental innovation. Similarly, Szymańska (2016) pointed out that urban eco-innovation requires coordinated actions across governance, funding, and citizen engagement. However, the present study extends these frameworks by demonstrating that institutional capacity and administrative competence at the local level remain the decisive variables in the Polish context.

In comparison to other studies (Hojnik & Ruzzier, 2016; OECD, 2011; UN-Habitat, 2020), the results show that while the policy environment in Poland aligns with the European Green Deal, there is still a significant implementation gap. This confirms the observation made by the European Commission (2023) in *the Eco-Innovation Scoreboard*, where Poland ranked below the EU average. Our research identifies that this gap arises not only from financial constraints but also from fragmented governance and low awareness among decision-makers.

Compared with earlier works that focused mainly on technological or environmental determinants, this study contributes new empirical knowledge by linking eco-innovation with governance capacity and local participation. This perspective highlights the importance of cities as learning systems, where institutional learning is combined with social experimentation. The case studies from Warszawa, Kraków, Wrocław, Łódź, Rzeszów, and Gliwice illustrate that eco-innovations become effective only when local governments integrate technology deployment with participatory approaches and long-term planning. This finding extends the conceptual framework of urban eco-innovation beyond the technological dimension toward a socio-institutional model.

Our analyses provide an integrated view of eco-innovation processes in Polish cities and show their broader implications for urban development and sustainability governance. In general, the results confirm the initial hypothesis that institutional integration and social awareness are key drivers of eco-innovation. However, the study also reveals that Poland's urban policies remain overly centralized, which slows down the diffusion of innovation. Decentralization of decision-making, combined with stronger financial incentives for municipalities, could significantly enhance the practical implementation of eco-innovations.

In relation to previous research, the novelty of this study lies in identifying governance-based eco-innovation as an emerging model of urban sustainability in Central Europe. While previous studies by Horbach et al. (2012) and Hojnik & Ruzzier (2016) analysed primarily the technological and economic dimensions, this paper demonstrates the interdependence between institutional capacity, civic participation, and adaptive management. The results also expand

the theoretical framework of eco-innovation by including urban governance, planning, and data-driven management as central determinants of success.

Furthermore, this study shows that eco-innovation should be considered not merely a technological process but a systemic transformation linking public policy, economy, and society. Similar conclusions were reached by Caragliu, Del Bo & Nijkamp (2011) and Batty et al. (2012) in the context of smart and sustainable cities. Polish cities follow this trend, albeit at a slower pace, gradually shifting from compliance-based policy models to adaptive and participatory governance frameworks.

The significance of this analysis lies in its interdisciplinary approach, combining perspectives from management, architecture, and data analysis. From the management perspective, eco-innovation requires coherent governance and institutional learning. From the perspective of urban design, cities act as physical laboratories where green infrastructure, compact spatial planning, and energy-efficient buildings demonstrate measurable benefits. Finally, from the data analytics perspective, smart systems, AI tools, and urban platforms enhance monitoring and decision-making, supporting long-term sustainability.

The study has certain limitations. The data were mainly derived from secondary sources and desk research, which may limit the precision of quantitative assessment. The case studies focused on large cities; smaller municipalities may face different institutional and financial conditions. Therefore, future research should include comparative quantitative analysis across cities of different sizes and governance capacities, combining GIS tools, data science, and social research methods.

In conclusion, the findings indicate that Poland's path toward sustainable urban transformation through eco-innovation is evolutionary rather than revolutionary. The effectiveness of eco-innovation depends less on technological advancement itself than on the ability to build coherent, participatory, and data-informed governance systems. This result confirms that the hypothesis formulated at the beginning of the study was correct and highlights the importance of integrating diverse disciplinary and sectoral perspectives to strengthen the adaptive capacity of cities.

8. Conclusions

Eco-innovations are most effective when implemented at the level of districts or entire cities, as this allows for scale and systemic impact. It is crucial to involve multiple stakeholder groups – residents, local authorities, scientific institutions and the private sector – in order to implement a coherent sustainability strategy. Educating the public is particularly important, as technology alone is not enough to achieve sustainable environmental effects. It is also necessary to change attitudes, habits and increase environmental awareness. In order for the

local community to really want to get involved, appropriate incentives are needed – both informative and financial. Financing models should be flexible and adapted to local realities and the level of acceptable risk, which increases their effectiveness and scalability.

Poland has a significant potential in the implementation of eco-innovations, both due to the scale of urbanization and the growing activity of local governments and civil society. There is also an increasing emphasis on climate education, the development of renewable energy sources, improving the energy efficiency of buildings and the modernization of public transport. These activities, supported by EU funds and local strategies, indicate a positive direction and growing readiness of Polish cities to implement comprehensive eco-innovations.

The determinants of urban eco-innovation are not a static category – their importance and nature can evolve with global technological, social and environmental trends. In the perspective of the coming decades, three megatrends will be of particular importance: digitization and artificial intelligence, climate and energy crises, and demographic change.

It should be emphasized that the development of digitalisation and artificial intelligence (AI)-based tools is radically changing the way eco-innovations are designed, monitored and implemented in cities. Intelligent energy management systems based on AI algorithms allow for real-time optimization of resource consumption by integrating renewable energy sources, energy storage and transport infrastructure. Thanks to the use of big data technology and the Internet of Things (IoT), it is possible to diagnose environmental problems more accurately – from air quality to effective waste management. The data collected from city sensors is the basis for better informed public policy decisions.

Another factor changing the face of eco-innovation is artificial intelligence, which is used, among other things, in modelling and predicting the effects of climate change, enabling the creation of spatial planning tools adapted to future threat scenarios. As a result, one of the key determinants of the development of eco-innovation is the city's ability to integrate digital solutions with technical infrastructure, public services and management systems. Cities that can effectively combine data, technology and spatial policy will be able to implement sustainable and efficient green solutions faster. In the face of increasing extreme events, such as droughts, floods or heatwaves, cities will need to prioritise innovations that increase the resilience of infrastructure and the ability to adapt to climate change. At the same time, global and regional energy crises will accelerate the transition towards autonomous, distributed energy systems, based on local renewable sources and energy storage.

The importance of eco-innovations in the area of energy efficiency of buildings, transport and municipal services will grow steadily, as they will be treated not only as a tool for environmental protection, but also as an element of energy security. In this context, crisis pressure will become a determinant of the implementation of eco-innovations, cities will be forced to accelerate the introduction of new technologies not only for ecological reasons, but also to ensure the continuity of infrastructure and the safety of residents.

Demographic changes, such as population ageing and increased internal and international migration, are becoming another factor influencing the direction of eco-innovation. An ageing population will force the design of solutions that support the accessibility and inclusiveness of urban space – from energy-efficient, ergonomic buildings adapted to the needs of older people to environmentally friendly forms of public transport that provide mobility for seniors. Migration, in turn, will increase pressure on urban infrastructure and municipal service systems, but at the same time create the potential for the development of eco-innovations that integrate diverse cultural and social needs. In multicultural cities, there will be a need to introduce social eco-innovations that support the integration of migrants and promote pro-ecological attitudes in diverse communities.

As a result, the ability of local governments to adapt green solutions to the needs of different social groups will become a determinant of eco-innovation in cities, which requires flexible planning, social dialogue and an inclusive approach to sustainable development. To sum up, the development of eco-innovation in cities in the coming years will be determined by three interdependent processes: digitization and the development of artificial intelligence, pressure resulting from the climate and energy crises, and demographic and social changes. What they have in common is the need for flexibility, adaptation and integration of technology into public policies. The cities of the future will not only be technologically smart, but also socially sustainable and environmentally resilient.

Beyond these practical implications, this research also contributes to the broader academic debate on sustainable urban transformation. It highlights that eco-innovation is not merely a technological trend but a governance paradigm linking environmental, economic, and social dimensions of urban development. The study offers a conceptual and empirical framework that can be used for comparative analyses across different European regions and governance systems.

Critically, the research recognises its own limitations. The findings are based mainly on qualitative analysis and secondary data, and further empirical studies – including quantitative evaluation, stakeholder surveys, and longitudinal monitoring – are necessary to assess the long-term effectiveness of eco-innovation policies.

Nevertheless, the lessons learned from the Polish context can inform both policy and practice across the EU. The results may support the refinement of cohesion policy instruments, inspire city-level strategies within programmes such as *Krajowa Polityka Miejska 2030* or *EU Mission: Climate-Neutral and Smart Cities*, and guide local authorities in designing flexible, data-informed, and inclusive innovation systems.

Ultimately, the research underscores the importance of adaptive governance – the ability of cities to learn, experiment, and evolve in response to environmental and social challenges. The knowledge generated in this study provides a foundation for further research and action, offering a roadmap for transforming eco-innovation from individual initiatives into an integrated mechanism for achieving long-term urban sustainability.

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