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Barriers and Drivers of Using Alternative Fertilizers in Sustainable Agriculture: Case Study of Poland

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Abstract

Fertilizers are crucial for enhancing soil fertility and agricultural productivity, playing a pivotal role in modern farming practices. However, the reliance on mineral fertilizers has raised concerns due to their environmental impacts, including soil degradation, water contamination, and greenhouse gas emissions. Consequently, there is growing interest in sustainable alternatives that leverage organic waste streams to recycle nutrients back into agricultural systems. Alternative fertilizers produced from such as sewage sludge, animal manure and digestate, are increasingly recognized for their potential to support sustainable agriculture. This paper presents the goal of assessing the current state and development potential of alternative fertilizer use in Poland in the context of circular economy (CE). The SWOT (strengths, weaknesses, opportunities, threats) method was used to carry out the analysis. The key findings include identification of strengths such as the environmental benefits of nutrient recycling, reduced waste generation and cost savings for farmers. However, the analysis also indicates weaknesses, such as inconsistent quality, potential contamination risks and social resistance to using waste-derived products. Opportunities were identified, including increasing demand for eco-friendly agricultural practices, technological advancements in waste treatment and supportive policies that promote CE initiatives. Nevertheless, the sector faces threats such as regulatory barriers, competition with synthetic fertilizers and potential health risks from pollutants in organic waste streams. Considering the rising importance of social dimensions in sustainability assessment, a growing number of studies in the fertilizer sector is expected to adopt Social Life Cycle Assessment (S-LCA) to evaluate social impacts and acceptance of alternative fertilizers.

Keywords Alternative fertilizers · Sewage sludge · Animal manure · Digestate · SWOT analysis · S-LCA analysis

Introduction

Fertilizers play a critical role in modern agriculture by enhancing soil fertility and ensuring high crop productivity (Babcock-Jackson et al. 2023). Since the mid-20th century, the widespread adoption of chemical fertilizers has been a major factor in increasing global food production to meet the needs of a growing population (Penuelas et al. 2023). These fertilizers, particularly rich in nitrogen (N), phosphorus (P), and potassium (K) compounds, provide essential nutrients that are often deficient in soils under intensive farming (Liu et al. 2024). However, an extensive use of chemical fertilizers has raised significant environmental concerns, such as soil degradation, water pollution from nutrient runoff, and greenhouse gas emissions from the production and application of these products (Hossain et al. 2022).

In response to these challenges, a growing interest in more sustainable agricultural practices, including the use of organic and so-called "alternative fertilizers" that are derived from secondary sources is observed (Riaz et al. 2021). Organic fertilizers, such as compost, manure and bio-based products, are increasingly viewed as environmentally friendly alternatives to conventional chemical fertilizers. These fertilizers not only supply nutrients but also contribute to the improvement of soil structure, water retention and biological activity, making them critical components of sustainable soil management (Kumari and Ranawat 2024). The alternative fertilizers gaining attention include sewage sludge (Smol et al. 2020a), animal manure and digestate ((Panuccio et al. 2018), bio-waste, slurry and municipal sewage sludge ash (Hauck et al. 2022). The

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dynamic development of waste-based products creates new business opportunities for the development of the fertilizer sector. However, this requires a thorough analysis of various factors that affect the profitability of such investments.

In the context of sustainable agriculture, fertilizers derived from secondary raw materials offer several advantages, primarily through nutrient recycling and reducing the extraction of primary raw materials, as phosphates (Kraj and Smol 2022). Sewage sludge, animal manure and digestate are notable examples of such materials that can be repurposed as fertilizers (Smol and Szołdrowska 2021). They reduce waste disposal needs as well as return valuable nutrients to the soil, contributing to circular economy (CE) principles by closing nutrient loops (Kvakkestad et al. 2023). The various studies have shown that these kinds of fertilizers could provide sufficient levels of N, P and organic matter, supporting plant growth and enhancing soil health (Di Costanzo et al. 2021).

In the European Union (EU), the interests in the use of alternative fertilizers varies across member states. For example, fertilizers produced from municipal sewage sludge ash (SSA) are permitted for use in Germany (Hauck et al. 2022), Austria (Adam et al. 2009) and Sweden (Ekane et al. 2021), while in Poland they are listed as substances unknown in use (Smol et al. 2020b). However, due to the requirements of the European Green Deal (European Commission 2019a), farmers in all European countries are obliged to intensify the use of waste-based materials (Pawłowski and Sołtysiak 2024). This also applies to Poland which is one of the largest producers of fertilizers in the EU, with a share of 18%, while being the largest producer of nitrogen fertilizers (20.3%) (Pawlak and Poczta 2025). In the coming years, the use of alternative materials to produce fertilizers, i.e., those derived from waste, is expected to increase. This is due to several recommendations for sustainable agriculture, particularly in regions with intensive agricultural activities (Babcock-Jackson et al. 2023). This paper presents an analysis of internal and external factors conditioning the development possibilities of the alternative fertilizers market, taking into account three groups of waste – sewage sludge, animal manure and digestate, which have the greatest potential for management in agriculture in Poland. These waste groups were selected for analysis because an extensive agricultural activities, the country generates substantial amounts of those organic wastes from both livestock production and municipal wastewater treatment (Komor and Bujanowicz-Haraś 2020). Currently, there are many methods and technologies for using these wastes as alternative fertilizers, such as composting, anaerobic digestion, mechanical separation or thermal drying. These processes enable the transformation of organic waste into fertilizers, improving soil health and reducing reliance on synthetic fertilizers (Tambone et al. 2010; Bernal et al. 2009; Möller and Müller 2012). However, the practical implementation of these products on the market is very challenging and requires a detailed analysis of various conditions, including regulatory barriers, public perceptions and technical limitations, which affect the wider adoption of these fertilizers in Poland (Łuczka and Kalinowski 2020). The development of the alternative fertilizers market faces several documented challenges, including competition from conventional mineral fertilizers, regulatory complexity and social skepticism. Mineral fertilizers continue to dominate due to their established supply chains, predictable composition and ease of use, which makes them more attractive to farmers (Piwowar 2022). Moreover, the rise of sustainability narratives has increased the risk of greenwashing, which may lead to stakeholder distrust if misleading claims about environmental benefits are made (Sciortino et al. 2025). Regulatory uncertainty - especially concerning sewage sludge and digestate - is another important barrier, as evolving legislation can impose administrative burdens and financial risks (Kurniawati et al. 2023). Additionally, the lack of standardization and quality control in animal manure use complicates its broader agricultural application (Jones and Deuss 2024).

While these studies provide valuable insights into individual barriers, there is still a lack of integrative analyses that assess all major waste-derived fertilizer types through a coherent strategic framework. This study addresses that gap by applying a SWOT analysis to three key waste streams - sewage sludge, animal manure and digestate -within the context of Poland's agri-environmental and regulatory system.

Therefore, this paper presents set of internal and external factors that were defined based on areas indicated in the analysis of strengths, weaknesses, opportunities and threats (SWOT). It is a strategic analysis tool used in companies and economic sectors to make appropriate business decisions and provide the best direction for the development of the company and the sector (Gürel and Akkoç 2011).

The work is structured in six sections. The first section discusses the importance of developing the alternative fertilizer sector and provides background information. The second section indicates research procedures, including a description of materials and methods used in this study. The next section presents research results, including: I) an overview of the fertilizer sector in Poland; II) the importance of the secondary fertilizer production sector; III) the results of the SWOT analysis for three groups of waste - sewage sludge, animal manure and digestate. This section also provides discussion of obtained results. The fourth section contains a future direction for alternative fertilizer sector in Poland. The fifth section describes implications of the study, and the sixth section presents conclusions from this work.

Methods

The research was conducted in three phases, employing a combination of desk research, SWOT analysis, and expert evaluation to assess the current state and development potential of the Polish fertilizer sector. The methodological approach aimed to identify key barriers, driving forces, and strategic solutions for the implementation of CE principles in this field, as outlined in the following sections.

Research Procedures

The first phase of the research involved an analysis of existing data, employing the desk research method (Smol et al. 2020d) to diagnose the current state of the Polish fertilizer sector and identify potential solutions to support its further development.

A systematic review of scientific literature and gray literature was conducted. The sources included peer-reviewed articles available in databases such as BazTech, the Polish Scientific Bibliography, Elsevier Scopus, Elsevier Science Direct, the Multidisciplinary Digital Publishing Institute (MDPI), and Google Scholar. Additionally, reports published by Polish organizations involved in fertilizer production and waste management as well as legal acts issued by the European Commission and national authorities were analyzed to ensure a comprehensive assessment of the analyzed aspects. When searching for scientific studies that analyzed various aspects of implementing alternative fertilizers from secondary sources in agriculture, the following keywords were used: "alternative fertilizers," "sewage sludge," "animal manure," "digestate," "SWOT analysis," "Poland area," "circular economy," "CE," "waste," "secondary sources," "agriculture".

This phase of the research also included an analysis of the Polish fertilizer sector, as the subsequent phase of the study focused on SWOT analysis of using alternative fertilizers. The analysis of existing data allowed for the identification of both the barriers and incentives affecting the development and implementation of alternative fertilizers in Poland.

The second phase of the research focused on the analysis of the current state of alternative fertilizers use in Poland, with particular attention to its driving forces and barriers. This assessment was carried out using a SWOT analysis, which allowed for the evaluation of four key aspects influencing the development of the fertilizer sector: strengths, weaknesses, opportunities, and threats. The aim of this analysis was to identify both internal factors (strengths and weaknesses) and external factors (opportunities and threats) that either support or hinder the further advancement of the alternative fertilizer sector in Poland.

SWOT analysis was selected due to its suitability for early-phase, expert-informed strategic assessments in areas undergoing complex systemic change. To minimize the typical limitations of the method, including subjectivity and lack of factor weighting, a structured scoring system was applied, followed by an expert panel discussion to validate, and prioritize the identified factors. Moreover, this method was chosen to answer the following research questions: (I) what are the key barriers to the development of alternative fertilizers in Poland?; (II) what are the driving forces and incentives for their implementation in the fertilizer sector?

The SWOT analysis recommended method of strategic management to identify strengths, weaknesses, opportunities and threats of a specific project or general business plan. And it is an effective tool in innovation management to evaluate the possibilities of introducing different products to the market, in our case alternative fertilizers coming from different waste streams. The primary objective of a SWOT analysis is to identify barriers and success factors, with a particular focus on regional economic aspects, research and innovation potential, and market penetration and exploitation (Benzaghta et al. 2021). The SWOT matrix, encompassing strengths, weaknesses, opportunities, and threats, serves as a highly effective analytical tool utilized by organizations and decision-makers to guide strategic processes. Its fundamental purpose is to enhance understanding of the various factors influencing business decisions or the development of a business strategy (Aldehayyat and Anchor 2008). To achieve this, SWOT systematically examines both the internal and external environments, identifying elements that may affect the feasibility or success of a decision. While widely employed by businesses, the methodology is equally applicable to non-profit organizations and, to a lesser extent, individuals for personal evaluations (Helms and Nixon 2010). Moreover, it is frequently used to assess initiatives, products or projects Fig. 1.

In order to conduct a SWOT analysis, the regional context regarding the production and use of alternative fertilizing products was first examined. Subsequently, a preliminary list of SWOT elements was prepared and shared with the members of the Regional Working Group (RWG) of the Novafert project. This group consists of representatives from non-governmental organizations (NGOs), national public institutions, businesses, universities, the agricultural sector, research centers and regional public administration. The experts were selected based on criteria outlined in the regulations of the Regional Working Groups of the Novafert project. The SWOT analysis was prepared in an Excel spreadsheet, which was then emailed to the experts. The members of the RWG assessed the SWOT elements by assigning scores based on predefined criteria. This process converted qualitative data into quantitative values using a scale from 1 to 5:

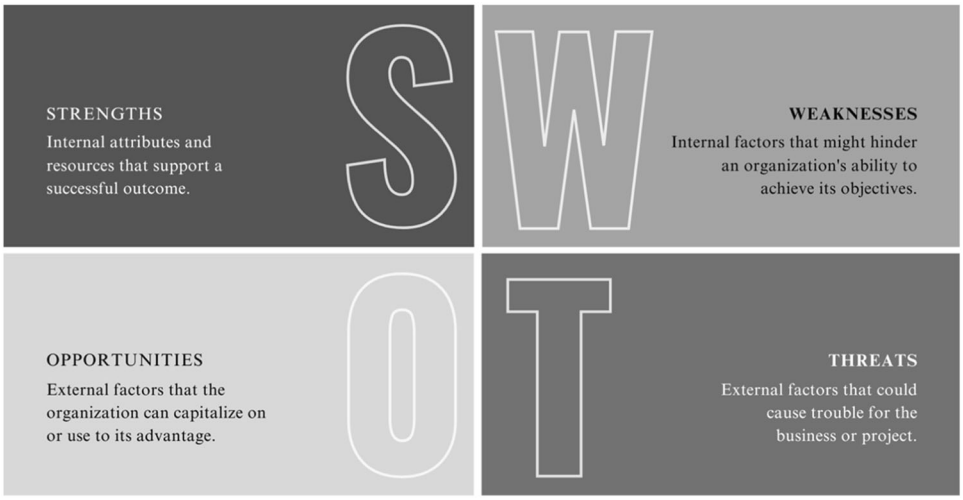

Fig. 1 SWOT matrix

- 1 point – not relevant (strength, weakness, opportunity, or threat),
- 2 points – weak relevance,
- 3 points – medium relevance,
- 4 points – relevant,
- 5 points – very relevant.

Following this, an expert panel was organized to discuss and refine the elements of the SWOT analysis.

The expert panel comprised seven specialists from various fields, carefully selected to ensure a comprehensive and balanced perspective. The participants included representatives from NGOs, public institutions, businesses, academic environments, the agricultural sector, research centers, and regional administration. Experts were chosen based on clearly defined criteria, including a minimum of five years of professional experience in the agriculture or fertilizer sector. Additionally, gender and sectoral parity were ensured to maintain a well-balanced representation of perspectives. This structured approach allowed for a thorough and objective evaluation of the SWOT attributes. During the expert panel, all factors indicated in the individual SWOT elements were discussed, and the final scores were assigned to them. The discussion was moderated by a delegated expert, who was then responsible for finalizing the Excel file with the results. The verified version of the SWOT analysis was sent by email to these experts, with a request for final comments or suggestions. No additional comments were made. The results of the SWOT analysis are presented in this paper, in the results section.

Case Study Analysis – Poland as a Research Area

Poland, officially known as the Republic of Poland, is a democratic country in Central Europe. Its capital and largest city is Warsaw. With a land area of 31,393,361 hectares (Budzyński et al. 2014), Poland is the ninth-largest country in Europe and ranks 69th among the world's largest countries. Poland shares its northern border with Russia (Kaliningrad Oblast) and Lithuania, its eastern border with Belarus and Ukraine, its southern border with Slovakia and the Czech Republic, and its western border with Germany (Statistics Poland 2024a). Geographically, Poland is a lowland country. Catholics are by far the largest religion in the country (Ciecieląg et al. 2022). According to the latest available data, Poland's population is approximately 38,324,214 (United Nations 2025a). This makes Poland the 42nd most populous country globally. In Europe, Poland ranks 7th in terms of population size (United Nations 2025b). The average population density is 122 inhabitants per square kilometer, although it is strongly varied between the relatively densely populated south and the north. In cities, 22.9 million people live (60%), while in rural areas, there are 15.3 million (40%) (Statistics Poland 2022a). Poland is quite homogeneous in terms of ethnic origin. National minorities, of which there are nine, constitute about 5% of the entire society. The largest ethnic minorities are Ukrainian, German, Belarusian, and Roma. Outside the country, there are about 21 million people of Polish descent, with over 10 million settling in the United States.

Agriculture plays a significant role in Poland's economy (Kowalczyk and Kwasek 2020). The fertile soils and favorable climatic conditions support a variety of agricultural activities. Moreover, Poland is one of the main agricultural producers in the EU: it belongs to the three largest producers of basic cereals and root crops and is also the largest supplier of apples and poultry meat (Statistics Poland 2022b). Agricultural land occupies an area of 18,418 thousand hectares, which accounts for 58% of the country's surface. The largest percentage of agricultural land is arable land, as it is as much as 76.4%, followed by fields - almost 13%, then pastures and orchards. Major agricultural

Table 1 Characteristic of fertilizers used in Poland (Filipiak 2024)

Fertilizer type	Fertilizer name	Composition (N-P-K)	Average price (PLN/ton)
Nitrogen fertilizer	Ammonium nitrate 34%	34-0-0	1080–1680
	CAN (Calcium Ammonium Nitrate)	27-0-0	1250–1540
	Urea	46-0-0	1680–5600
	Urea with urease inhibitor 46%	46-0-0	1850–2220
	Coated urea 46%	46-0-0	1400–2500
	UAN (Urea-Ammonium Nitrate Solution) 32%	32-0-0	1100–1580
Phosphorus fertilizers	Single superphosphate (granulated)	0-19-0	1230–1800
	Enriched superphosphate	0-40-0	1360–2600
	Diammonium phosphate (DAP)/ Polidap 18/46%	0-18/46-0	1780–3300
Potassium fertilizers	Potassium chloride (MOP) 60%	0-0-60	1480–1900
	Potassium sulfate 50%	0-0-50	1520–4000
Multi-component fertilizers	Polifoska	8-24-24	2280–2800
	Polifoska	6-20-30	1450–1920
	Calcium Ammonium Nitrate	27-0-0	1450–1920
	Amofoska	4-16-18	1000–2500

products include cereals (such as wheat, barley and rye), potatoes, sugar beets and vegetables. Livestock farming, including cattle, pigs, and poultry, is also an important part of the agricultural sector.

Results and Discussion

The section presents the results of the research and discussion.

Overview of Conventional Fertilizer Sector in Poland

The fertilizer sector in Poland plays a crucial role in ensuring agricultural productivity and food security. The consumption of mineral fertilizers in Poland is one of the highest in Europe (Piwowar 2018). Moreover, according to data from the Statistics Poland, areas used for agricultural production to produce safe and high-quality food account for nearly half of the country's total land area, highlighting the importance of the fertilizer sector in maintaining the efficiency of these lands (Statistics Poland 2024b). As a leading producer and consumer of fertilizers in Central and Eastern Europe, Poland's market is shaped by domestic production capacities, international trade and EU regulations. This part of paper provides an overview of the sector, examining key producers, market trends, regulatory frameworks, and an analysis of fertilizer types, compositions and pricing.

Poland's fertilizer market is dominated by several major companies, including Grupa Azoty and Anwil S.A. which together account for over 80% of the country's fertilizer production. Grupa Azoty, one of the largest chemical groups in Europe, accounts for a significant share of nitrogen and compound fertilizer production (Azoty Group Fosfory Sp. z o.o. 2024). The country's agricultural sector, characterized by a mix of large-scale commercial farms and smaller family-owned holdings, drives consistent demand for fertilizers (Anwil S.A. n.d.).

Table 1 summarizes common fertilizers used in Poland, their composition, and indicative market prices.

In recent years, the total consumption of mineral fertilizers in Poland has remained high (Piwowar 2018). According to data from the Polish Ministry of Agriculture and Rural Development, the total country consumption of mineral fertilizers (in terms of pure ingredient) per hectare of agricultural land was 123.10 kg/ha, with nitrogen-based fertilizers being the most widely used. In the 2022/23 farming year, consumption figures included: nitrogen fertilizers: 70.70 kg/ha, phosphorus fertilizers: 19.30 kg/ha, potassium fertilizers: 31.90 kg/ha (Statistics Poland 2024c).

Despite the steady demand for fertilizers in Poland (Piwowar 2022), the industry faces several challenges, including rising production costs due to fluctuations in energy prices (Gołasa et al. 2022), particularly natural gas (Kowalska et al. 2024), which impact fertilizer production expenses. Environmental concerns also play a significant role, as increasing pressure to reduce nitrogen runoff and

carbon emissions is pushing the sector towards more sustainable solutions, such as organic fertilizers (Panday et al. 2024). Additionally, geopolitical factors, such as dependence on imported raw materials, affect supply chain stability. In response to supply chain disruptions, Poland has intensified efforts to invest in phosphate recovery technologies and alternative fertilizer production methods, such as using sewage sludge (Smol et al. 2020b, 2016) and digestate in agriculture.

As a member of the EU, Poland adheres to EU directives regulating fertilizer production, distribution, and environmental impact. One of the key regulations is Regulation (EU) 2019/1009, which establishes rules for the marketing of fertilizers within the EU, ensuring product safety, proper labeling, and environmental compliance (The European Commission 2019). Another important document is Directive 91/676/EEC (Nitrates Directive), aimed at preventing water pollution caused by excessive fertilizer use (The European Council 1991). At the national level, the National Fertilizer Act (2020) sets specific rules on the production, trade, and use of fertilizers in Poland, aligning with EU policies (Sejm of the Republic of Poland 2007). These regulations ensure that fertilizer products comply with environmental and agronomic standards while promoting sustainable farming practices. Additionally, under the European Green Deal's "Farm to Fork" strategy (European Commission 2020a, 2019a), Poland is required to reduce fertilizer use by at least 20% by 2030 and increase reliance on organic alternatives. These regulations allow the use of waste materials to produce fertilizers and soil improvers, while maintaining appropriate quality indicators.

Importance of the Secondary Fertilizer Production Sector

The fertilizer sector is increasingly incorporating secondary raw materials derived from various waste streams as a sustainable alternative to mineral fertilizers. This shift, driven by the principles of the CE (European Commission 2020b), aims to recover valuable nutrients, reduce waste generation and minimize the environmental footprint of fertilizer production. Secondary fertilizers produced from sources such as manure, sewage sludge and digestate are gaining attention for their ability to enhance soil fertility and support sustainable agricultural practices. However, their adoption is subject to various economic, environmental, and regulatory considerations.

In Poland, the utilization of secondary fertilizers is influenced by economic (Kowalska et al. 2024), environmental and regulatory factors. These factors influence the adoption and development of sustainable practices in the agricultural sector. Among the various available options, animal manure, sewage sludge and digestate have been identified as the most viable alternatives due to their availability, nutrient content, and alignment with national agricultural and waste management policies.

Sewage sludge, a by-product of wastewater treatment, is increasingly being considered as an alternative fertilizer in Poland (Sejm of the Republic of Poland 2022). It contains significant quantities of organic matter, nitrogen, and phosphorus, which can enhance soil fertility (Jakubus 2024) (Gusiatin et al. 2024). However, concerns about the presence of heavy metals, pathogens and microplastics have limited its widespread acceptance (Pozzebon and Seifert 2023). Poland's legal framework, guided by both national and the EU regulations, tightly controls the use of sewage sludge in agriculture to minimize environmental risks (Przydatek and Wota 2020). The Waste Act (Sejm of the Republic of Poland 2022) and the Regulation of the Minister of Environment of 6 February 2015 on municipal sewage sludge (Minister of the Environment, 2015) in Poland establish strict criteria for the quality of sludge and the conditions under which it can be applied to agricultural land. Additionally, amendments to the EU's Sewage Sludge Directive (European Commission 1986) may impose even stricter limits on contaminants, further shaping the regulatory landscape. Despite these challenges, the benefits of sewage sludge use in agriculture cannot be overlooked (Sugurbekova et al. 2023). Research shows that when appropriately treated, sewage sludge can significantly improve soil organic matter and nutrient content, thereby reducing the need for synthetic fertilizers (Grobelak et al. 2024). Moreover, the use of sludge as a fertilizer contributes to waste minimization goals and promotes a circular approach to resource management (Paganini et al. 2024). Poland is identified as a region where treated sewage sludge can be used in agriculture, particularly in crop production.

Animal manure has long been a traditional fertilizer in Polish agriculture, especially in regions with significant livestock production. Animal manure is rich in organic matter and nutrients, particularly nitrogen and phosphorus, making it an excellent soil conditioner (Kopiński and Wrzaszcz 2020). Poland produces substantial amounts of manure, primarily from pig, cattle, and poultry farms, which are widely used in cereal crop production. Management of animal manure must comply with the provisions of the Regulation (EC) No 1069/2009 of the European Parliament and the Council of 21 October 2009, which establishes health rules for animal by-products and derived products not intended for human consumption, and repeals Regulation (EC) No. 1774/2002 (Animal By-Products Regulation). Additionally, it must adhere to Regulation (EC) No. 142/2011 of 25 February 2011, which implements Regulation No. 1069/2009, laying down health rules for animal by-products and derived products not intended for human

consumption and implementing Council Directive 97/78/EC regarding certain samples and items exempt from veterinary checks at the border under that Directive. Moreover, the Fertilizers and Fertilization Act (Sejm of the Republic of Poland 2007) governs the use of manure, ensuring that it meets quality standards and is applied in a manner that minimizes environmental harm. One of the key benefits of manure is its cost-effectiveness, as it requires relatively low processing compared to synthetic alternatives (Ren et al. 2023), making it an attractive option for farmers in Poland. However, it is associated with challenges such as odor and storage difficulties, which can limit its scalability.

Digestate, a by-product of the anaerobic digestion of organic matter, including animal manure, is another emerging waste in Poland. Digestate is often used in biogas production (Lamolinara et al. 2022), and after the extraction of biogas, the remaining material is rich in nutrients (Ehmann et al. 2018). Although digestate contains fewer contaminants than untreated sewage sludge, its application is still subject to regulatory scrutiny under the Waste Act (Sejm of the Republic of Poland 2022) and the Fertilizers and Fertilization Act (Sejm of the Republic of Poland 2007) in Poland. Moreover, its adoption is hindered by high processing costs and logistical barriers, including transportation and storage requirements (Farghali et al. 2022). Nonetheless, research indicates that digestate can be a valuable fertilizer, particularly in improving soil organic carbon and nutrient content.

In general, described above waste materials, as composts, sewage sludge, animal manure, digestate are expected to play an increasingly significant role in market of alternative fertilizer in Poland and the EU (European Commission 2020c). The adoption of such materials not only represents a step toward more environmentally sustainable solutions but also offers an opportunity to reduce dependence on raw material imports, particularly from unstable regions (Smol and Szołdrowska 2021). By 2030, it is estimated that at least 25% of fertilizers used in Poland will come from organic and recycled sources, in alignment with the EU's CE goals (European Commission 2020c). In comparison, alternative fertilizers such as manure were applied to approximately 18% of Polish farmland in 2018–2019. Based on this and other national data, it is estimated that organic and recycled fertilizers currently represent approximately 8–10% of total fertilizer use in Poland (Kopiński and Wrzaszcz 2020). Investment in innovative technologies and a sustainable approach to resource management could contribute to the long-term growth and stability of the Polish fertilizer market (Mroczkowski 2021).

SWOT Analysis

The integration of alternative fertilizers derived from secondary raw materials such as sewage sludge, animal manure, and digestate into Polish agriculture presents a multifaceted landscape of advantages (Smol et al. 2016) and challenges (Panday et al. 2024). These fertilizers align with the principles of a CE (European Commission 2020c) by recycling nutrients back into the soil, thereby enhancing soil health and reducing reliance on synthetic fertilizers. However, their adoption is impeded by regulatory complexities, social perceptions, and economic considerations (Álvarez Salas et al. 2024).

This section provides an overview of the strengths and weaknesses, as well as the opportunities and threats associated with the implementation of alternative fertilizers in the agricultural sector, along with the importance of these factors (both internal and external) for the further implementation and development of alternative fertilizers (from sewage sludge, animal manure and digestate) in Poland. The results of the SWOT analysis are shown in a collective tables that displays the identified strengths, weaknesses (Table 2), opportunities and threats (Table 3). These factors, both positive (strengths, opportunities) as well as negative (weaknesses, threats), were assigned appropriate weights by the experts involved in the study.

Based on the identified key strengths, it can be concluded that alternative fertilizers offer significant advantages in terms of sustainability, safety and economic feasibility. Their positive ecological image makes them an attractive option, as they support the principles of a CE (European Commission 2020c, 2019a) and align with the increasing environmental awareness in modern agriculture. Furthermore, application security is ensured by strict regulations (European Commission 2019b), which guarantee that these fertilizers meet safety standards and do not pose risks to soil, crops, or human health. Another notable benefit is their soil improvement potential, as they enhance soil structure, increase organic matter content, and promote microbial activity, contributing to long-term soil fertility (Álvarez Salas et al. 2024; Diacono and Montemurro 2015). Another important advantage is the soil improvement benefits resulting from the organic matter present in these fertilizers. This aligns with existing literature that underscores the long-term benefits of organic fertilization in maintaining soil productivity and microbial diversity (Álvarez Salas et al. 2024). An important advantage is their self-sufficiency, as the availability of organic materials such as sewage sludge and animal manure reduce dependency on imported synthetic fertilizers (Chew et al. 2019). In addition, these materials are widely accessible on the Polish market, facilitating their use in agricultural production. From an economic perspective, the competitive pricing of sewage sludge-based fertilizers make them a cost-effective alternative to mineral fertilizers, encouraging their broader adoption. Moreover, the low processing costs of animal

Table 2 SWOT analysis of the alternative fertilizers in Poland – internal factors

Elements	Description	Scoring		
		Sewage sludge	Animal manure	Digestate
Strenght	**Availability on the market** In Poland, sewage sludge, digestate, and animal manure are available in the market. Poland has a well-developed wastewater treatment sector, which translates into the availability of sewage sludge. Animal manure is commonly used in agriculture in Poland, particularly in cereal crops and animal husbandry. Digestate, is also available in Poland, but on a smaller scale	5	4	1
	Price The price of fertilizers from secondary sources such as sewage sludge, animal manure and digestate in Poland is relatively low. The most expensive is fertilizer made from animal manure, followed by digestate and sewage sludge	5	2	3
	Easy of application The application of fertilizers derived from sewage sludge, digestate and animal manure is relatively easy in Poland and does not require advanced technology	4	4	4
	Low processing costs Processing costs are low for manure as opposed to sewage sludge and digestate	1	5	1
	Legislative standpoint From a legislative standpoint, the application of fertilizers derived from sewage animal manure is straightforward in Poland, unlike digestate and sewage sludge, where the procedures are complicated	1	5	1
	Soil health improvement Fertilizers from sewage sludge, digestate and animal manure enrich the soil by enhancing its nutrient content and improving microbial activity. They contain beneficial microorganisms, increase nutrient availability, and enhance soil structure	4	5	5
	Application security The application of fertilizers derived from sewage sludge, digestate and animal manure is safe because regulated by law	5	4	5
	Ecological image of fertilizers Society is increasingly paying attention to the ecological aspects of fertilizers. Fertilizers made from sewage sludge, digestate and animal manure are part of the idea of ecological products	5	5	5
	Resource self-sufficiency (local production) The possibility of producing fertilizers from waste at their place of generation	4	5	4
	Soil hydrological improvement Reducing the adverse effects of drought	4	4	4
	Stable, precisely planned production stream The amount of biomass produced in a treatment plant, fermentation plant or farm is easy to plan	5	4	3
Weaknesses	**High installation costs** High installation costs for sewage sludge and digestate	4	1	4
	Society's unwillingness Society often shows reluctance towards products made from waste	5	1	4
	Unstable composition The difficulty of maintaining a stable composition of fertilizers derived from sewage sludge, digestate and animal manure	4	2	2
	Necessity of quality control Products made from sewage sludge, digestate and animal manure must undergo quality control	4	1	3
	Legal restrictions There are legal restrictions on the use of fertilizers from sewage sludge, animal manure and digestate	5	1	4
	Storage difficulty There is a difficulty in storing products made from waste	5	4	4
	Raw material availability Sewage sludge cannot be transported between voivodeships. Additionally, production must be located close to the place of generation	4	4	4
	Unpleasant odor The unpleasant odor discourages consumers from buying and using waste fertilizers	2	5	2

manure further increase its attractiveness as a sustainable fertilizer solution (Ren et al. 2023).

Regarding weaknesses, storage difficulties were identified as a significant drawback across all waste streams, as organic fertilizers require specialized facilities to prevent nutrient loss and environmental impact. Sustainable storage solutions can be costly and space-consuming, creating obstacles for farmers and suppliers. Another major challenge is raw material availability, which is further complicated by transportation difficulties between provinces. The inconsistent supply of organic fertilizer components due to logistical constraints, seasonal variations, and regulatory limitations makes it difficult for farmers to rely on these fertilizers as a stable alternative to mineral-based products (Panday et al. 2024). Additionally, social reluctance was identified as a key weakness, particularly concerning sewage sludge and digestate. Public perception of these materials remains negative due to concerns about

Table 3 SWOT analysis of the alternative fertilizers in Poland – external factors

Elements	Description	Scoring		
		Sewage sludge	Animal manure	Digestate
Opportunities	**Recommendations at the level of the EU** Recommendations at EU level on the use of fertilizers from waste	5	5	5
	Legal regulations Legal regulations at the national and European level regarding fertilizers from waste	1	1	1
	Market gap Market gap regarding the rising price of mineral fertilizers	1	1	1
	Decreasing availability of critical raw materials Biogenic nutrients, including phosphorus, are on the list of European critical raw materials, but also key critical raw materials for Poland	5	5	5
	Circular waste management Possibility to reduce waste generation and the opportunity to implement CE solutions in practice	5	5	5
	Research and development Continued investment in research and development can lead to the development of more effective and specialized fertilizers based on waste tailored to the specific needs of Polish soils and crops	5	4	5
	Implementation installations Financial support for implementation installations	4	3	4
	Environmental awareness Increasing ecological awareness among Polish society	4	5	5
	Growing market for secondary raw materials Increasing use of secondary raw materials	5	5	5
	Demand for ecological products Growing demand for ecological products by consumers	5	5	5
	Development of technologies/innovation Due to the prohibition of sludge storage, technologies to produce fertilizers are being intensively developed	1	5	1
Threats	**Regulatory challenges** The regulatory landscape surrounding alternative fertilizers, including registration, certification, and labeling requirements, can pose challenges for manufacturers and distributors	5	2	4
	Lack of standardization and quality control The production and distribution of alternative fertilizers may face challenges related to quality control and standardization. Ensuring consistent quality and efficacy of alternative fertilizers is essential to gain trust from farmers and promote their wider adoption. Any lapses in quality control can undermine the credibility and hinder the growth of the alternative fertilizer industry	2	5	3
	Competing technologies and products Fertilizers from waste face competition from other agricultural technologies and products, including synthetic fertilizers, precision farming techniques, and genetically modified crops. The availability and aggressive marketing of these alternatives may pose challenges to the widespread adoption of alternative fertilizers	5	5	5
	Environmental pollution Risks of environmental pollution from microplastics, pharmaceuticals and other substances	4	3	2
	Environmental risk Possibility of environmental pollution due to improper storage, processing and use of secondary raw materials	3	3	3
	Threat of greenwashing The appearance of false information about other technologies that are considered greener and cheaper than sewage sludge, digestate and animal manure treatment methods	4	4	4
	Uncertain legislative future The sewage sludge directive has been revised and will most likely be updated. There may be more stringent quality requirements. In addition, the law on the control of micropollutants is tightened	5	2	4

contamination, odors, and potential health risks, which do not apply to animal manure to the same extent (Ekane et al. 2021). Addressing these concerns requires campaigns and transparent safety measures to enhance acceptance among farmers and consumers. From an economic and operational standpoint, sewage sludge and digestate face high installation costs and strict quality control requirements, making their adoption more demanding than that of animal manure. Processing these materials must comply with stringent safety and environmental standards, necessitating significant investments in infrastructure and monitoring systems. Furthermore, legal restrictions on sewage sludge and digestate impose additional burdens, as complex regulatory frameworks govern their use, transportation, and treatment. Compliance with these regulations can be both time-consuming and costly, further limiting their widespread application (Giwa et al. 2023). On the other hand, odor issues emerged as a significant drawback specific to animal manure. The strong and persistent smell associated with manure-based fertilizers present practical challenges

for storage, transportation, and field application, often leading to complaints from nearby communities and requiring odor-mitigation strategies.

Despite these challenges, alternative fertilizers offer various opportunities but also face external threats, which are outlined in Table 3.

The analysis of opportunities revealed several shared prospects for all waste streams. One of the most significant drivers is EU recommendations encouraging the use of alternative fertilizers, which promote the transition towards more sustainable agricultural practices, e.g. the EU's Farm to Fork Strategy aims to reduce nutrient losses by 50% by 2030 while preserving soil fertility, thereby reducing reliance on synthetic fertilizers and fostering the adoption of organic and waste-derived alternatives (European Commission 2020a). Another crucial factor is the growing demand for ecological products, both among consumers and within the agricultural sector. As awareness of environmental sustainability increases, farmers are more inclined to adopt fertilizers that align with CE principles (European Commission 2020c). At the same time, the decreasing availability of critical raw materials (European Commission 2020d), particularly phosphorus, highlights the urgent need for alternative sources of nutrients (Smol et al. 2022). The recovery of critical elements from waste streams is increasingly recognized as essential for long-term resource security and the development of the CE models. The growing secondary raw materials market reinforces the role of alternative fertilizers derived from organic waste. Technological advancements, particularly in the treatment of animal manure, enhance the safety, quality, and competitiveness of these products. Continued investment in research and infrastructure is pivotal for their broader adoption in sustainable agricultural systems. On the other hand, the development and adoption of alternative fertilizers in Poland face several external threats, particularly in the areas of market competition, regulatory uncertainty and quality control (Łuczka and Kalinowski 2020).

One of the key risks is competition with other technologies and products, as mineral fertilizers and other established solutions continue to dominate the agricultural sector. Their well-developed supply chains, consistent composition, and ease of use make it challenging for alternative fertilizers to gain widespread acceptance among farmers (Piwowar 2022). Another significant concern is the growing issue of greenwashing and misinformation about green technologies. As sustainability becomes a key focus in agriculture, misleading claims about the environmental benefits of certain products may lead to distrust among consumers and stakeholders. Without clear and transparent communication, alternative fertilizers could face skepticism, slowing down their market adoption (Sciortino et al. 2025). Additionally, regulatory challenges and an uncertain legislative future for sewage sludge and digestate create obstacles for producers and users. Changes in environmental policies, evolving safety requirements, and complex legal frameworks may impose additional costs and administrative burdens. The lack of long-term regulatory clarity makes investment in these fertilizers riskier and less attractive to businesses (Kurniawati et al. 2023). Finally, the lack of standardization and quality control for animal manure remains a pressing issue. Unlike mineral fertilizers, which have well-defined nutrient compositions, animal manure varies in quality depending on its source and processing methods. Without uniform standards and strict quality regulations, its effectiveness as a fertilizer may be inconsistent, limiting its large-scale adoption (Jones and Deuss 2024). The results of this SWOT analysis are consistent with the findings of other researchers, highlighting the significant benefits of using alternative fertilizers but also the numerous barriers to their implementation. Legal issues, competition from mineral fertilizers and social reluctance are recurring challenges that may hinder their wider application in agricultural practice.

Recommended Directions for the Alternative Fertilizer Sector in Poland

The effective implementation of alternative fertilizers require a comprehensive approach encompassing legislative changes, technological development, public education and logistics optimization. Only the combination of these efforts can lead to an increased use of waste in fertilizer production and contribute to more sustainable agriculture in Poland.

A key priority is the development of organic waste processing technologies. Methods such as composting, anaerobic digestion and sewage sludge drying enhance the fertilizing properties of these materials while minimizing the risks associated with the presence of pathogens and heavy metals (Smol et al. 2020b). Investing in innovative technologies can contribute to increasing the efficiency and safety of alternative fertilizers. Another important aspect is the modification of legal regulations, which should facilitate the safe and efficient use of alternative fertilizers such as manure, digestate, and sewage sludge (European Commission 2020b). Current legislation often imposes restrictions on their application, hindering their widespread use in agriculture (Ministry of Agriculture and Rural Development 2022). Simplifying certification procedures and adjusting quality standards to align with current technological capabilities could significantly accelerate the development of this sector. Equally significant is education and changing the attitudes of farmers and consumers. Concerns about the quality and safety of fertilizers derived from waste still exist, which limits their market acceptance. Informational

Table 4 Importance of individual aspects in SWOT analysis of using alternative fertilizers from secondary sources

SWOT area	Average scores in analyzed waste		
	Sewage sludge	Animal manure	Digestate
Strengths	3.9	4.0	3.8
Weaknesses	4.1	2.3	3.4
Opportunities	3.7	4.0	3.8
Threats	4.0	3.4	3.6

campaigns and training programs could help break down stereotypes and promote the adoption of these solutions among users.

Additionally, changes are needed in the logistics and distribution system. Alternative fertilizers often have large volumes and variable composition, which can complicate their transport and storage. Infrastructure support, such as the creation of local distribution centers or the development of storage systems, could improve the availability of these fertilizers and increase their attractiveness to farmers.

Implications of Study and Future Directions

The results presented in this paper, focusing on the analysis of various aspects of using alternative fertilizers from secondary sources, may be important to entities operating in the agriculture and waste management sectors. The identified strengths indicate the potential for utilizing sewage sludge, animal manure and digestate as valuable fertilizers, which may contribute to improving the nutrient balance in the soil and increasing the efficiency of the CE.

Nevertheless, the analysis of weaknesses highlights the differences between the various types of alternative fertilizers (Table 4). Sewage sludge exhibits the highest proportion of weaknesses, which may result from challenges related to its chemical composition, legal limitations and public perception regarding its use. On the other hand, animal manure presents the fewest significant barriers, suggesting that its use is relatively easier and more accepted in the agricultural sector.

The identification of opportunities indicates that analyzed alternative fertilizers possess significant development potential. High ratings in this category suggest the possibility of better utilization of these resources within the framework of the CE concept. Animal manure and digestate can serve as important sources of nutrients and organic matter for the soil. On the other hand, the identified threats highlight existing barriers to the broader application of these fertilizers, with the greatest concerns relating to sewage sludge. This may be due to legal regulations and potential environmental and health risks associated with the presence of heavy metals and other contaminants. Nevertheless, the relatively lower threat levels for animal manure and digestate suggest that their utilization may be more promising, particularly in the context of the growing interest in sustainable agriculture. In the context of existing threats, it is necessary to implement additional technological solutions and assessment methods that also consider social aspects that affect social acceptance and the decision-making of stakeholders.

In recent years, Life Cycle Assessment (LCA) has become increasingly important in assessing waste management technologies, enabling a comprehensive analysis of environmental impacts throughout their entire life cycle – from raw material extraction to the end-of-life stage, including potential reuse (Smol et al. 2020c). In the context of fertilizers produced from waste, the extended Life Cycle Sustainability Assessment (LCSA) approach is increasingly used, which integrates three key areas: environmental, economic and social. The economic dimension can be carried out using Life Cycle Cost Assessment (LCCA), which facilitates the estimation of capital investment, operational, and maintenance costs. The social aspect is analyzed using Social LCA (S-LCA), which allows for taking into account the impact of technology on the health, safety and well-being of local communities, employees or consumers (UNEP/SETAC 2012). Despite its growing relevance, there is a limited number of papers in the scientific literature on the application of the S-LCA method in relation to the production of fertilizers from waste. Considering the growing importance of social issues in the implementation of the European Green Deal (European Commission 2019a) policy and the growing pressure to implement sustainable solutions, one can expect an intensification of research using the full sustainability-LCA approach.

The final results of the SWOT analysis (Table 5) indicate a significant predominance of opportunities and strengths over threats and weaknesses, which is a positive signal for the further development of the alternative fertilizers market. Therefore, the key direction for future changes should involve the introduction of innovative technological solutions aimed at eliminating contaminants, as well as increasing social acceptance and regulatory support for these fertilizers. In this context, the S-LCA method can crucial role, which – despite its limited use in the waste-based fertilizer sector so far – is a valuable method for identifying and assessing the social conditions of implemented technologies. Considering social factors such as occupational safety, impact on local communities or consumer perception of products will be relevant for shaping

Table 5 Final SWOT matrix summarizing key strategic factors influencing the development of the alternative fertilizers market in Poland

Strength	Weaknesses
• High availability of organic waste (sewage sludge, manure, digestate)	• Inconsistent composition and quality of organic fertilizers,
• Potential for nutrient recovery and circular economy benefits	• Limited public awareness and trust,
• Support from EU policies promoting bioeconomy and waste valorization	• Technical barriers in processing and application,
• Growing demand for sustainable farming practices	• Lack of harmonized standards and quality control,
• Existing research and innovation capacity in Poland	• Logistical and storage challenges.
Opportunities	**Threats**
• New regulations encouraging organic waste reuse,	• Strong market dominance of mineral fertilizers,
• Increasing pressure to reduce greenhouse gas emissions and overall environmental impact,	• Unclear or changing legal framework for organic fertilizers use,
• Potential for green innovation and bio-based products,	• Risk of greenwashing and stakeholder skepticism,
• Access to EU funding for sustainable agriculture.	• Price volatility and investment uncertainty in emerging fertilizer sector.

future directions of sustainable development in agriculture and waste management.

Conclusions

Fertilizers, essential for soil fertility and agricultural productivity, have historically relied on mineral sources. However, their environmental impacts, such as soil degradation, water contamination and greenhouse gas emissions, have driven interest in sustainable alternatives. Organic fertilizers derived from secondary raw materials, like sewage sludge, animal manure and digestate, offer sustainable solutions by recycling nutrients, reducing waste and decreasing reliance on environmentally harmful mineral fertilizers. The document emphasizes the growing adoption of such practices in Poland.

The critical strengths of alternative fertilizers, as identified in the research, include their positive ecological image, which reflects growing societal and consumer interest in sustainable farming practices. Regulations ensure the secure application of these fertilizers, thereby mitigating environmental risks and building trust among stakeholders. These fertilizers offer significant benefits for soil improvement by enhancing nutrient content and promoting microbial activity, which are essential for long-term agricultural productivity. Another notable strength is the self-sufficiency achieved through the local availability and production of these fertilizers, reducing dependency on imported synthetic alternatives.

In addition, the market availability of sewage sludge and animal manure provides a reliable resource base for farmers, while competitive pricing makes sewage sludge-based fertilizers particularly appealing. Low processing costs for animal manure further enhance its feasibility as an economically viable option, contributing to cost savings for agricultural operations. Together, these factors create a robust foundation for the integration of alternative fertilizers into sustainable farming practices, aligning with both ecological goals and economic imperatives. These strengths underscore the potential of alternative fertilizers, such as sewage sludge, animal manure, and digestate, to contribute meaningfully to the transition towards sustainable agriculture, particularly in regions like Poland, where extensive agricultural activities necessitate innovative and environmentally friendly solutions. By addressing existing challenges and leveraging identified strengths, these fertilizers can play a pivotal role in reducing waste, enhancing soil health, and promoting CE principles in the agricultural sector.

Furthermore, to ensure the sustainable integration of these fertilizers, it is essential to assess not only environmental and economic factors, but also the broader social implications of their use. The application of S-LCA provides a structured approach for evaluating social impacts across the value chain — including aspects such as worker health and safety, community well-being, and stakeholder perception. Although S-LCA remains underutilized in the context of fertilizer production from waste, its relevance is expected to grow, especially in light of increasing emphasis on social responsibility.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Author Contributions Conceptualization PM, MS, Data curation PM, Methodology PM, MS, Supervision MS, Visualization PM, Writing – original draft PM, Writing – review and editing PM, MS.

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Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

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