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# A Closed-Loop Economy in the Meat Industry for Generating Alternative Energy from Biogas Plants

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**Abstract:** This study deals with the concept of a closed-loop economy in the meat industry through the use of animal by-products in biogas plants for electricity generation processes. The purpose of the study was to identify the volume of by-products from the slaughter of cattle and pigs, how the by-products are managed, and the efficiency of their use in biogas plants for electricity production processes. The analyses used data from the Central Statistical Office, the Chief Veterinary Inspectorate, and information obtained from the Polish Agency for Enterprise Development. Studies from the literature on closed-loop economies and bioeconomies were also a valuable source of information. Based on case studies, this paper also presents examples of a closed-loop economy in meat companies. In the area of pork, poultry, and beef livestock production, the analysis covered the years 2004–2022, while in the area of the production and use of meat industry by-products, the data came from 2017–2022. The study shows that reducing the production of waste in the meat industry and the reuse and recycling of waste are important parts of a closed-loop economy. In meat companies, waste from slaughtering animals can be properly managed, either by processing it into animal feed or by using it in biogas plants to generate electricity or heat. Taking into account the number of by-products from cattle and pig slaughter in the country, biogas plants could produce approximately 95,232 MW of electricity per year, which constitutes approximately 4.3% of the energy intensity of the meat industry in Poland.

**Keywords:** energy; animal by-products; waste; meat industry; biogas plants; closed-loop economy

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## 1. Introduction

A closed-loop economy is a model of operation that involves reducing waste and reusing and recycling products for as long as possible, thereby extending their life cycle in the economy. It is a concept that aims to extend the life of extracted raw materials, as well as existing products, and minimize waste production while maintaining continuous economic development [1]. The concept covers all stages of a product's life cycle: design, production, consumption, collection, and waste management. Signals et al. state [2] that the closed-loop economy mainly refers to physical and tangible resources—focusing on recycling, reducing, and reusing physical inputs to the economy and using waste as a resource, leading to the reduced consumption of primary resources. One of the goals of the closed-loop economy is to reduce energy-intensive activities, raw materials, and water, in addition to minimizing waste and air pollution [3].

The closed-loop economy embraces the 3-R (reduce, reuse, recycle) philosophy. This system assumes that every material can be recycled, and that energy should come from renewable sources. All actions in this direction strengthen and restore the ecosystem and promote the health of society, and resources are properly used to generate value [4].

In line with the European Green Deal's goal of achieving EU climate neutrality by 2050, the European Commission proposed a new closed economy roadmap in March

2020. It focuses on waste prevention and management and aims to boost the EU's growth and competitiveness in this area. The indicated measures are a practical reflection of the assumptions of sustainable development economics, which seeks to define economic conditions that move beyond the perspective of short-term profits and take into account natural and socio-cultural conditions [5]. A real change in the current model will only be possible if the transition to a closed-loop economy includes all sectors of the economy, but of particular importance in this regard will be the sectors and industries that are most dependent on the consumption of primary raw materials and generate the largest amounts of waste [6]. This group includes the meat industry, which is expected to minimize waste, use resources efficiently, and maximize value recovery from animal by-products.

The primary products of meat companies are raw meat and meat products. This production is accompanied by animal by-products, which are materials of animal origin that are not intended for human consumption or that people do not consume. They account for 60% of animal weight, of which 40% is edible and 20% inedible. In the case of beef, pork, and lamb, by-products comprise 10–30% of the body weight, and in the case of poultry meat, by-products comprise 5–6% [7]. Animal by-products are produced by slaughterhouses, meat processors, wholesalers, and rendering plants. More than half of animal by-products are not suitable for normal consumption due to their unusual physical and chemical properties. As a result, a valuable source of potential income is lost and the cost of disposing of these products increases. In addition to economic losses, unused meat products are a major environmental pollutant [8].

Such products can be used in the plants themselves or in other entities, such as the following: rendering plants, carnivorous fur farms, or pet-food companies, where they produce pet food (for dogs and cats), contributing to the creation of a closed-cycle economy. Thus, animal by-products do not have to generate additional costs for meat plants due to the need to dispose of them. They can become a potential raw material for management in biogas plants or pet food companies, among others. Meat industry enterprises are closely linked to animal production carried out on farms, which are the primary raw material base for entities in this sector. There are also meat enterprises on the market that develop their raw material base in the form of fattening plants.

The efficient use of animal by-products has a direct impact on the economy and the reduction of environmental pollution. On the other hand, the underutilization of by-products leads to additional waste disposal costs, as well as the loss of potential revenue [8].

The study formulated two research objectives:

1. Recognizing the volume of production of animal by-products and ways to manage them;
2. Determining the volume of electricity production from the by-products of cattle and pig slaughtering in biogas plants.

The study consists of six chapters. The first presents the rationale for undertaking the presented research topic. The second reviews the literature on the topic of closed-loop economies in the food industry. The third chapter presents the data sources and research methodology. The next part of the study covers the results of the research. In this regard, the energy intensity of meat industry production is presented in comparison with other food industries, as well as the volume of products generated in the meat industry, the use of these -products, the calculation of energy production from by-products of the slaughter of cattle and pigs, and examples of companies applying a closed-loop economy in the meat industry. The discussion includes the role and importance of biogas plants in the agri-food sector, the limitations of their operation, and the possibilities of financial support for this type of investment. The paper concludes with conclusions and recommendations on closed-loop economies in the meat industry, as well as limitations and suggestions for further research.

## 2. Review of Literature on Closed-Loop Economies

The transition to a closed-loop economy is attracting increasing interest, especially in the food industry. This is because it is a very good sector to initiate this kind of transformation due to its high resource consumption and significant contribution to waste

generation. At the same time, global challenges that significantly affect the food production system include food waste, resource scarcity, and environmental degradation. According to researchers Yontar [9], Jabbour et al. [10], Abbate et al. [11], and Diéguez-Santana et al. [12], the potential development of agriculture and food production can be ensured and sustained through the use of a circular economy, especially in the food sector. In this context, resource utilization, waste reduction, and sustainability are the goals of a circular economy strategy.

Implementing a closed-loop economy enables more efficient use of resources and less waste throughout the product life cycle, from raw material acquisition to production and consumption [13]. Implementing closed-loop economy principles in the food industry helps mitigate climate change by reducing greenhouse gas emissions, optimizing energy consumption, and minimizing the environmental impact of food production and distribution [14]. According to Abbate et al. [11], the concept of a closed-loop economy can help maintain good environmental quality by reducing carbon emissions for food production. In addition, applying such a concept can lead to the sustainability of production and supply chains, as well as the creation of better food systems. It enables the use of less energy and helps reduce greenhouse gas emissions by minimizing pollution and resources. Applying the concept of a closed-loop economy to food production is key to reducing waste, using resources more efficiently, and ultimately achieving the Sustainable Development Goals. The closed-loop economy approach further supports the economy and the environment by enabling healthy products made from food waste to reach new consumers.

The circular economy is increasingly linked to the bioeconomy as both concepts aim to achieve the sustainable use of natural resources and minimize waste [15]. The bioeconomy is based on the innovative use of sustainable biological resources to meet the growing demand of the food, energy, and industrial sectors while protecting the environment. As the world population continues to grow against a backdrop of limited natural resources, renewable biological resources are needed to provide healthy food and animal feed, materials, and other biological products such as biofuels [16]. According to the European Commission report [17], the bioeconomy encompasses the production of renewable biological resources and the transformation of these resources and waste streams into value-added products such as food, feed, biological products, and bioenergy. The concept uses research and innovation in the biological sciences to create economic activity and benefits for society [18]. According to the OECD definition, the bioeconomy applies biotechnology, bioprocesses, and bioproducts to develop sustainable, ecologically sound, and competitive products and services. It includes three elements: biotechnological knowledge, renewable biomass, and their applications in different types of production activities [19].

Meat waste is an important topic in the context of the bioeconomy because it is a part of organic waste that can be used in different biological processing methods, which is in line with the idea of sustainable resource management. The bioeconomy is based on the use of renewable biological resources for the production of food, energy, bioproducts, and other resources, which in the case of meat waste may include processes such as biotransformation, recycling, or biogas production. However, it is crucial to properly manage this waste to avoid health and environmental risks and to implement appropriate processing technologies. Food and feed safety can only be ensured through shared responsibility between the suppliers and processors of animal by-product materials, the compound feed industry, and livestock producers [20].

The circular economy and bioeconomy are considered important elements within the architecture of the Green Deal [21]. The relationship between the value of the closed-loop economy and sustainability has been studied by Kumar et al. [22], Knäble et al. [23], and Patyal et al. [24]. They show that the application of the concept contributes to achieving development in three dimensions: economic, social, and environmental.

An important part of closed-loop economy research related to the food industry is efforts to reduce the consumption of natural resources in the food production process [25,26]. In this regard, it is important to recognize the work of the engineers who have contributed to the creation of eco-industrial parks, which make good use of the concepts of industrial

ecology and symbiosis [27]. In turn, research in economics and management shows how to integrate the concepts of sustainability and a circular economy at different levels [28].

The approach to the circular economy is mainly oriented toward market and financial benefits. A study by Mehmood et al. [29] shows that the most important factors motivating the adoption of closed-loop economy methods in the agri-food supply chain include environmental, political, economic, and financial benefits. In contrast, the main obstacles to implementing closed-loop economy concepts are related to institutional, financial, and technical risks. Máté et al. [30] proved from their research that food production companies that follow cost-effective and sustainable practices have higher levels of profitability. This was also confirmed by the results of studies by Abbate et al. [11], Ramos et al. [31], and Cuesta-Gonzalez and Morales-García [32].

Szűcs, Vanó, and Korsós-Schlesser's research indicated a great desire to overcome the difficulties food processors face in obtaining necessary inputs and fostering long-term cooperation between farmers, intermediary agencies, and food processing companies. In their view, sustainable production procedures, less waste, and the optimal use of resources form the basis of a closed-loop economy strategy for food companies [33].

Earlier studies mostly examined individual aspects of sustainability and waste management [34,35]. Current analyses focus on specific areas, such as reducing food waste [36,37], resource efficiency [38,39], and technological advances in waste processing [40,41]. To a lesser extent, research is focused on the feasibility of applying the closed-loop economy to meat companies, which are among the most energy-intensive in the food industry. The prepared study fills the research gap in this area.

## 3. Materials and Methods

The subject of the study was the application of the concept of a closed-loop economy in the meat industry through the use of animal by-products in biogas plants for electricity production processes. The analyses used data from the Central Statistical Office, the Central Veterinary Institute, and information obtained from the Polish Agency for Enterprise Development. Studies from the literature on the closed-loop economy in the food industry were also a valuable source of information. In the area of production energy intensity, the analysis covered the years 2004–2022, while in the area of the production and use of meat industry by-products, the data came from 2017–2022. To determine the efficiency of using animal by-products in biogas plants to produce electricity, a calculator posted on the website of the BioGas System company from Katowice [42] was used. The indicated company specializes in designing and building biogas plants using technology that allows for the most efficient production of biogas from the most available organic materials. The company offers comprehensive biogas solutions, tailored to various industry needs and specifications. The calculator developed by the company enables interested entities to assess the potential benefits of using a specific substrate, taking into account its quantity. The biogas calculator is an online tool that allows you to accurately calculate potential biogas production based on different types of substrates. After entering the amount of the given substrates, the calculator automatically provides the results.

The analyses also used the results of a study conducted in 2023 among a group of 400 enterprises on the potential of a closed-loop economy, commissioned by Stean Recycling. A case study method was used in the presentation of examples of a closed-loop economy in meat enterprises. The results of the research are presented in descriptive, graphical, and tabular form.

## 4. Results

### *4.1. Energy Intensity of Meat Industry Production Compared to Other Food Industries*

Energy consumption is one of the key production factors in any industry. It has a particularly large impact on the efficiency of meat processing plants and the environment. The amount of energy consumption depends on many factors, such as the scale and structure of production, the technology used, the thermophysical properties of raw materials, the mechanization of production processes, and the use of processing capacity [43–53].

The food industry, which includes the production of foodstuffs and the production of beverages, is one of the most energy-intensive branches of industrial processing in Poland. In 2022, companies in this sector consumed 99,201 Terajoules (TJ) of electricity, ranking fourth among the most energy-intensive processing departments, behind enterprises engaged in the production of the following: (1) coke and refined petroleum products (242,862 TJ), (2) chemicals and chemical products (176,662 TJ), and (3) other non-metallic mineral products (133,272 TJ).

The most energy-intensive processing division in Poland's food industry is the meat industry. Between 2004 and 2022, its share in terms of the total energy intensity of production sold increased by 3.5 percentage points to 24.3%, i.e., 2226.3 Gigawatt hours (GW). On the other hand, the sector's average production energy intensity per PLN 100 of production value (at current prices) in 2022 fell to 2.2 kW, i.e., by more than half compared to 2004 (4.7 kW) (Table 1). This was mainly due to the nearly 4-fold increase in the value of the meat industry's sold production during this period, which significantly reduced the fixed unit energy consumption of enterprises, but also the average total energy consumption per PLN 100 of production value. In constant prices, the sector's energy consumption decreased by 0.6 kW (from 2.8 to 2.2 kW per PLN 100 of sold production value), i.e., by 21.4%. In 2022, the average energy intensity in the meat industry, per PLN 100 of sold production value, was 0.4 kW lower than the average in the food industry (in 2004, the difference was 0.7 kW).

Reducing energy consumption is influenced by the efficient use of energy, i.e., the rational and sustainable management of both the energy itself and the raw materials used to produce it. Improving production efficiency reduces the growth in demand for fuels and energy and reduces the adverse effects of energy on the environment and human health by reducing greenhouse gas emissions [54]. Many countries are recognizing that energy efficiency benefits national security, as energy imports from abroad can be reduced and use from domestic sources can be reduced through energy efficiency gains [55]. Energy sources can include animal by-products, which are generated in large quantities in the meat industry, especially in slaughterhouses. They provide a valuable substrate in biogas plants for the production of biogas, which is used to generate electricity and heat.

**Table 1.** Food industry sold production [a] and energy intensity of production [b] (in medium and large companies).

| Specification | 2004 | 2022 | Change (Percent) 2022–2004 | 2004 | 2022 | 2004 | 2022 | Change (Percent) 2022–2004 |
|---|---|---|---|---|---|---|---|---|
| | Value of Production Sold (Million PLN) | | | Energy Intensity of Sold Production (kW/100$^3$) Sold Production) | | Total Energy Intensity of Sold Production (Thousand MW) | | |
| Production of food and beverages, including the following: | 87,481.7 | 339,203.4 | 287.7 | 5.4 | 2.7 | 4724.01 | 9158.49 | 93.9 |
| groceries | 76,044.8 | 331,505.9 | 312.3 | 5.6 | 2.7 | 4258.51 | 8464.66 | 98.8 |
| beverages | 11,436.9 | 25,697.5 | 124.7 | 4.2 | 2.4 | 480.35 | 616.74 | 28.4 |
| Selected activities, including the following: | | | | | | | | |
| production, processing, and preserving of meat and meat products | 20,870.0 | 101,197.2 | 384.9 | 4.7 | 2.2 | 980.89 | 2226.34 | 127.0 |
| fish processing and preservation | 2342.7 | 17,008.8 | 626.0 | 3.4 | 1.5 | 79.65 | 25.13 | 220.3 |
| fruit and vegetable processing, including the following: | 8635.3 | 23,954.3 | 177.4 | 9.0 | 4.0 | 777.18 | 958.17 | 23.3 |
| • potato processing and canning; | 1322.5 | 2742.2 | 107.3 | 7.5 | 3.8 | 99.19 | 104.20 | 5.1 |
| • production of fruit and vegetable juices; | 2284.0 | 7117.9 | 211.6 | 4.8 | 2.9 | 109.63 | 206.42 | 88.3 |
| • processing and preserving fruits and vegetables | 5028.8 | 14,094.2 | 180.3 | 11.4 | 4.6 | 573.28 | 648.33 | 13.1 |
| manufacture of dairy products, including the following: | 14,871.0 | 54,307.3 | 265.2 | 4.8 | 2.3 | 713.81 | 1249.07 | 75.0 |
| • milk processing and cheese making; | 14,377.7 | 52,020.6 | 261.8 | 4.5 | 2.1 | 647.10 | 1092.43 | 53.5 |
| • ice cream production | 493.3 | 2286.7 | 363.6 | 12.7 | 7.4 | 62.65 | 169.22 | 68.8 |

[a] Value of production sold of food and beverages at current prices (excluding tobacco products). [b] Electricity consumption per PLN 100 of sold production at current prices. Source: [56,57].

### *4.2. Animal By-Products Resulting from the Meat Industry*

The amount of animal by-products generated in the meat industry is derived from the volume of animal production. Between 2004 and 2022, slaughter livestock production, which includes the three most important slaughter animal species, i.e., poultry, swine, and cattle, increased in Poland by almost 51% (from 4517 to 6805 thousand tons), an increase of 2.3% per year. The fastest growth was in poultry livestock production by 5.9% per year, reaching 3663 thousand tons in 2022. Beef livestock production increased by 52.4% to 1021 thousand tons, while pork livestock declined by 16.4% to 2121 thousand tons (Figure 1).

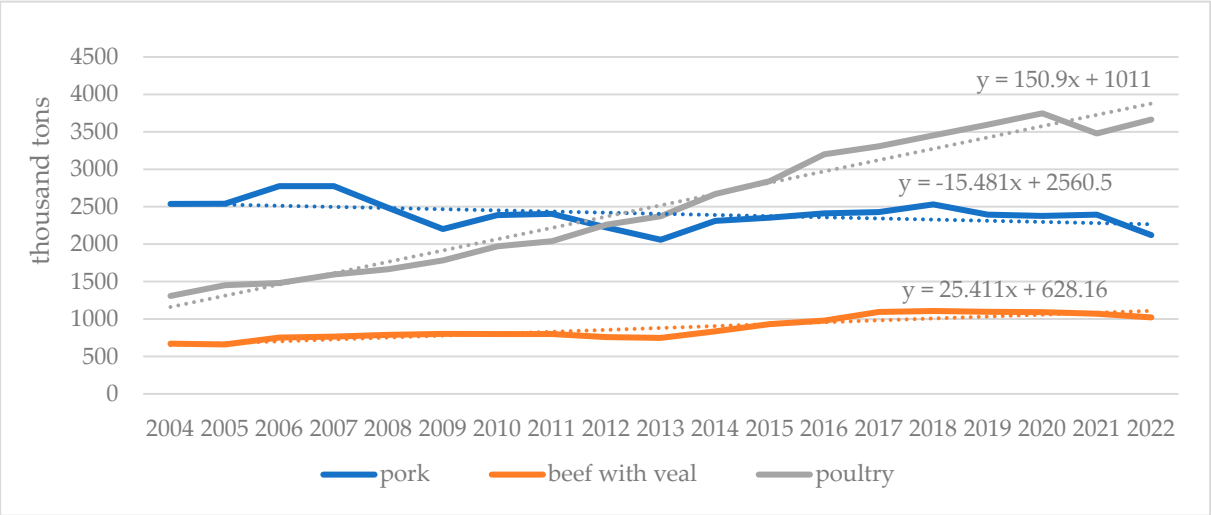



**Figure 1.** Pork, beef, and poultry livestock production in Poland from 2004 to 2022. Source: own compilation based on Statistical Yearbooks of Republic of Poland CSO from 2006–2023 [58–61].

The primary products of meat industry companies are raw meat and meat products. Derived from this production are animal by-products, which are primarily generated during the slaughter of animals and during the cutting of carcasses.

In addition to the scale of production, meat companies also differ in their production profile, as they can manage the following:

- running the full production cycle, i.e., slaughtering animals, cutting and processing;
- cutting with processing;
- the slaughter itself.

This diversification of the business profile generates the potential volume of animal by-products produced.

They are classified into three special categories, reflecting the level of risk to human and animal health:

1. Special risk material (Cat. 1)—risks associated with prions, use of prohibited substances, or environmental contaminants;
2. High-risk material (Cat. 2)—microbiological risks or risks associated with the presence of substances or contaminants over permissible levels;
3. Low-risk material (Cat. 3)—animal by-products from animals showing no signs of disease [62].

Detailed rules for the categorization and management of animal by-products in the EU are laid down in two regulations:

- Regulation (EC) No 1069/2009 of the European Parliament and of The Council of 21 October 2009, which outlines the health rules regarding animal by-products and derived products not intended for human consumption and repeals Regulation (EC) No 1774/2002 (Animal by-products Regulation) [63];

– Commission Regulation (EU) No 142/2011 of 25 February 2011, which implements Regulation (EC) No 1069/2009 of the European Parliament and of the Council, laying down health rules regarding 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 [64].

Between 2017 and 2022, the volume of unprocessed animal by-products (of all three categories) in Poland increased by 12.5%, from about 2.20 to 2.50 million tons (Table 2). The largest recipients of these products were processing (rendering) plants, whose share increased to 81.5% (i.e., by 7.4 percentage points). Pet food producers also strengthened their position to 10.1% (up 3.4 percentage points). In contrast, the share of carnivorous fur farms decreased by 10.6 percentage points to 8.4%.

**Table 2.** Amount of unprocessed animal by-products generated in Poland [a] (in thousand tons) by management by recipient groups.

| Listing | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|---|---|
| Processing (rendering) plants | 1625.61 | 1673.42 | 1777.16 | 1872.51 | 1899.32 | 2009.88 |
| Carnivorous fur farms and collection points for animal by-products; for carnivore feed production | 415.92 | 440.81 | 336.01 | 322.22 | 266.18 | 207.03 |
| Pet food manufacturers | 149.71 | 149.71 | 197.35 | 187.30 | 185.58 | 247.96 |
| Total | 2191.20 | 2263.94 | 2310.51 | 23,821.00 | 2351.08 | 2464.87 |

[a] No imports. Source: own compilation based on GIW data.

The structure of unprocessed animal by-products is dominated by Category 3 products generated primarily at meat processing plants. These include the following:

– carcasses or body parts of animals slaughtered in a slaughterhouse as fit for human consumption;
– products or food of animal origin originally intended for human consumption, but withdrawn for commercial reasons;
– animal hides, skins, hooves, feathers, wool, horns, and hair from animals that showed no signs of infectious disease at the time of slaughter [65].

The volume of animal by-products included in Category 3 and accepted at rendering plants in 2017–2022 increased from 1.32 million to 1.68 million tons (Table 3). During this period, animal by-products included in Category 1 accounted for a significantly smaller amount, with volumes ranging from 281.3 thousand to 289.4 thousand tons in 2017–2021. In 2022, their volume decreased to 261.6 thousand tons. The volume of animal by-products included in Category 2 in the years under review was many times smaller.

**Table 3.** Animal by-products accepted at processing (rendering) plants by category (in thousand tons).

| Material Categories | Years | | | | | |
|---|---|---|---|---|---|---|
| | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
| I | 281.34 | 286.17 | 286.91 | 289.60 | 289.44 | 261.58 |
| II | 27.95 | 11.66 | 8.67 | 9.96 | 58.27 | 69.31 |
| III | 1316.32 | 1375.59 | 1481.58 | 1572.95 | 1551.61 | 1678.99 |
| Total | 1625.61 | 1673.42 | 1777.16 | 1872.51 | 1899.32 | 2009.88 |

Source: own study based on unpublished data from the Chief Veterinary Inspectorate.

In the structure of animal by-products accepted at rendering plants, the share of products belonging to Category 3, i.e., low risk, in 2022, accounted for 83.5%, and the

remaining 16.5% was made up of animal by-products belonging to Categories 1 and 2. These came from, among other things: dead and diseased livestock, carcasses of animals killed to combat infectious diseases (ASF in pigs, or avian influenza among poultry), as well as carcasses of wild animals suspected of being infected with a disease, which were disposed of (Figure 2). Taking into account the fact that mainly Category 3 material goes from meat processing plants to carnivorous fur farms and pet food companies, its share of total unprocessed animal by-products accounted for more than 90%, or about 2.2 million tons, in 2022.

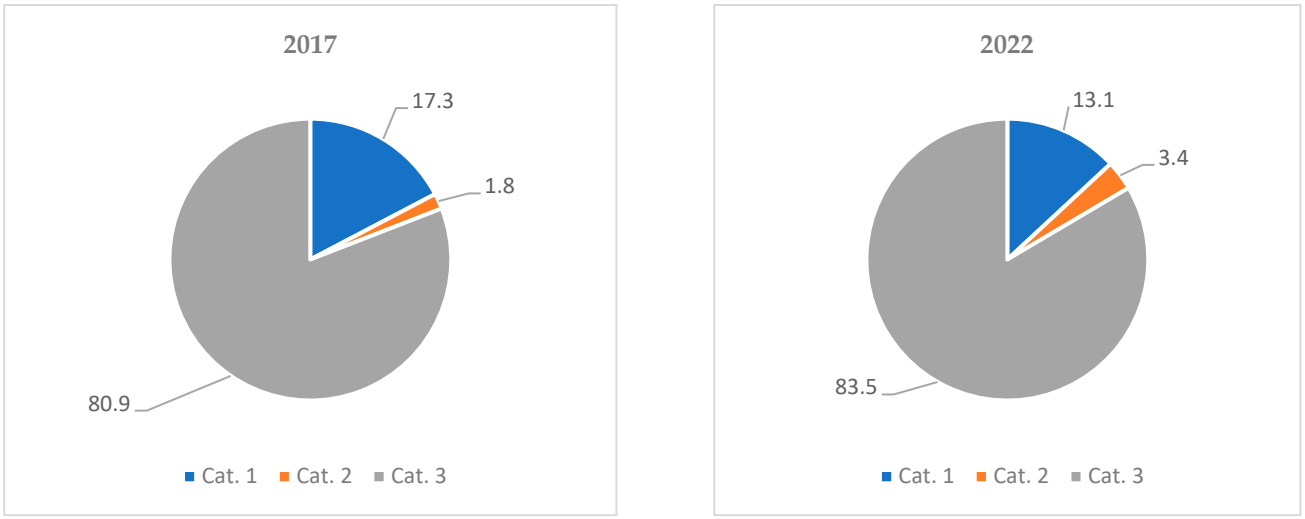



**Figure 2.** Structure of animal by-products accepted at rendering plants by category in 2017 and 2022. Source: own study based on unpublished data from the Chief Veterinary Inspectorate.

The management of unprocessed animal by-products can be carried out in many ways. Meat and bone meal produced from Category 1 material, i.e., among other things, from vicious livestock and wild animals bearing disease, from dead livestock containing special risk material, or from certain parts of the bodies of such animals, is an energy raw material intended to be burned mainly in cement plants or brickyards. Its calorific value is about 18 MJ/kg and is only about 20% lower than that of inferior quality eco-pea. Practically, this is the only way to manage such meals and is a reliable alternative to the coal burned in these enterprises. In 2022, about 64,000 tons of such meal were burned, which is marginal in comparison to the amount of coal burned annually, mainly for energy purposes [65]. Such a meal must have the right parameters, such as a certain proportion of fat so that screens do not clog and the combustion process runs smoothly. Appropriate machinery, presses, and high temperatures are needed to produce it. In addition to economic considerations, however, sanitary and epizootic aspects are more important here, as they is the only way to neutralize Category 1 material. When the first cases of bovine spongiform encephalopathy (BSE) were found in Poland at the end of the 20th century, the problem of managing so-called high-risk waste caused some slaughterhouses to stop slaughtering this species of livestock, as meat plants could not cope with the accumulated high-risk material.

Scientific research has led to the development of methods for detecting DNA from poultry and pigs, which in turn enables the control and monitoring of compliance with strict rules for the processing and cross-feeding of poultry and pig protein and its identification in feed materials and the feeds themselves. The development of such methods was one of the basic conditions for authorizing processed animal protein for feeding. In September 2021, the European Commission, in Regulation No. 1372 [66], allowed the limited use of selected materials from insect protein, poultry protein, and pig protein in feed for poultry, pigs (cross-feeding), and other farm animals, excluding ruminants [67]. However, the law still maintains an absolute ban on feeding farm animals with meat and bone meals produced from Category 1 and 2 material and any ruminant proteins. Only under strict restrictions

is cross-feeding allowed with non-ruminant proteins processed using the safest methods possible: cross-feeding from poultry—pigs and pigs—poultry. Animal by-products have a wide range of uses (Figure 3). They can be a source not only of processed valuable animal protein, classic meat and bone meals, or fats, but also of many other products. Modern developments make it possible to produce high-quality products, used in pharmaceuticals, cosmetics, and medicine. Heparin, gelatin, collagen, protein hydrolyzers, plasma, and red blood cells can be obtained from such by-products. The fats extracted by processing are widely used in the chemical industry as well as in feed and biofuel production [68].

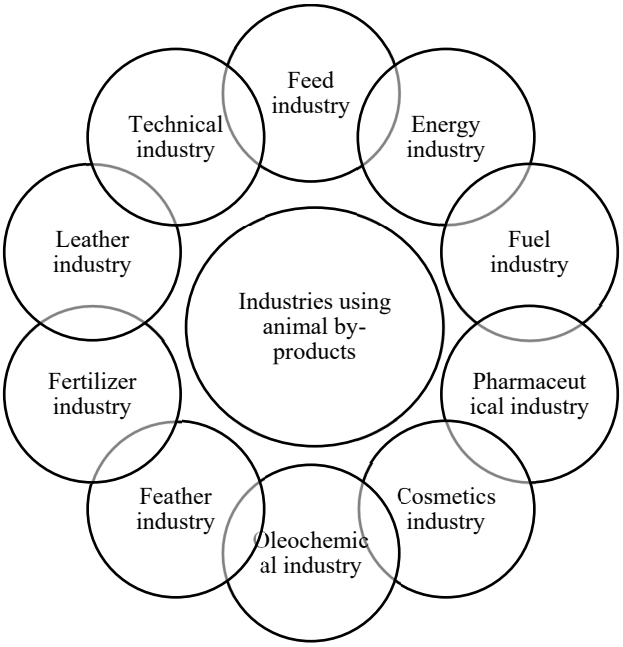



**Figure 3.** Possible uses for animal by-products. Source: [56].

In recent years, an average of about 1.85 million cattle and 20–22 million pigs were slaughtered annually in Poland [69,70]. The amount of food content remaining in the entire digestive tract, i.e., including the stomach in cattle and pigs, was determined after consultations with people from meat plants and scientists dealing with meat production technology. Assuming that the average content of the entire digestive tract of one adult head of cattle is 100–120 L, and that of pigs is 10–12 L, this results in 205 and 230 thousand tons of waste, respectively, which is a potential raw material for biogas plants, among others. Waste of this kind, or rather, by-products, is obtained at the stage of slaughtering animals in slaughterhouses, and in the next stage of production it is treated as a raw material (substrate), thus creating a closed circuit corresponding to the modern circular economy.

Substrates for a biogas plant can be various types of by-products from agricultural production and from the processing of agricultural raw materials. A detailed list of substrates that can be used in agricultural biogas plants is included in the regulation of the Minister of Agriculture and Rural Development of 12 October 2023 [71]. The resulting biogas from the fermentation of organic waste is a valuable source of energy. In meat processing plants, fermentation can be used to process waste such as blood, bones, fats, and animal proteins. In practice, however, it is limited due to the chemical composition of animal by-products. Proteins and fats are particularly difficult to decompose during fermentation. The effectiveness and safety of fermentation are influenced by the type of waste, water content, temperature and pH, and fermentation time [72].

For the proper operation of a biogas plant, the materials must be homogeneous, although it is possible to combine (mix) them. It is also important for meat companies that have decided to build a biogas plant to take into account its parameters, which determine

the type and amount of substrate supplied continuously. In Poland, cattle are slaughtered in about 300 plants and pigs in about 500 enterprises, with some entities slaughtering both animal species at the same time. However, the scale of slaughtering at the plants varies greatly, and in the case of cattle ranges from a few to several thousand head per week, and in the case of pigs from a few dozen to several thousand head per week.

One of the main obstacles to biogas exploitation is economic considerations. This problem applies to both biogas production from crops [73] and animal production substrates [74]. Studies in Italy have shown that for biogas from animal residues, the minimum capacity of a biogas plant to ensure profitability should be 200 kW, and for bio methane production, 350 $m^3$/h [75].

### *4.3. Calculation of Energy Production from By-Products of Cattle and Pig Slaughtering*

In order to recognize the possibility of using animal by-products to produce biogas and electricity, the results were calculated using substrates from slaughtered cattle and pigs. The most significant number of animal by-products from the slaughter of cattle and pigs is created at the slaughter stage. Therefore, it was assumed that the primary substrate for the biogas plant would be the contents of the digestive tracts of slaughtered cattle and pigs. Animal by-products included in Category 3, among others, have a more comprehensive application and are used by other entities. In the case of their use in a biogas plant, they must be subjected to additional heat treatment beforehand.

Table 4 shows the potential—maximum animal by-products obtained from slaughterhouses and sent to biogas plants. In reality, some animal by-products may end up in sewage and sewage treatment plants, mainly at the stage of slaughtering, and, to a lesser extent, at the stage of cutting half-carcasses and processing. Each plant processing animal by-products conducts separate sewage management, in terms of technical, technological, and organizational aspects, for domestic sewage (municipal sludge) and for products of animal origin from processing. Flotation sludge from sewage treatment plants may also be useful for biogas production. However, due to the lack of data and the difficulty in estimating the amount of animal by-products sent to sewage, only the content of the digestive tract of animals was taken into account in the analyses.

**Table 4.** Calculation of electricity production in biogas plants from by-products of cattle and pig slaughtering.

| Specification | Cattle | Pigs |
|---|---|---|
| Assumptions | | |
| Number of rammed pieces | 1000 pieces/week (52,000 pieces/year) | 8000 pieces/week (416,000 pieces/year) |
| Substrate for biogas plants | rumen content 5700 tons/year | tailings 4600 tons/year |
| Effects | | |
| Biogas production | 1222 Nm/day$^3$ | 1112 Nm/day$^3$ |
| Biogas production (annual) | 445,968 Nm/year$^3$ | 405,720 Nm/year$^3$ |
| Biogas production (hourly) | 50.91 Nm/h$^3$ | 46.32 Nm/h$^3$ |
| Electric power equivalent | 144.41 kW | 131.38 kW |
| Efficient power generation | (8000 h × 144.41 kW) 1155 MW | (8000 h × 131.38 kW) 1051 MW |

Source: own study.

Taking into account possible maintenance and downtime, the effective efficiency of the biogas plant is estimated at around 8000 h per year. With this assumption, the biogas plant could produce 1,155,200 kW or 1155 MW of electricity from the substrate from cattle

slaughter (post-flotation waste). With by-products from pig slaughtering (post-flotation waste), the biogas plant could produce 1,051,040 kW or 1051 MW of electricity.

Considering the potential amount of cattle slaughter by-products in the country at about 205,000 tons per year, biogas plants could produce about 41,540 MW of electricity. On the other hand, the potential number of by-products from the slaughter of pigs is estimated at 235,000 tons per year, which could produce about 53,692 MW of electricity.

If it were possible to direct the entire rumen content of all slaughtered cattle and flotation waste from pig slaughter to a biogas plant, approximately 95,232 MW of electricity could be produced annually. This volume of production accounts for about 4.3% of the energy intensity of the meat industry (red and white meat) in 2022. Taking into account the energy consumption of the poultry industry at about 489,800 MW, the electricity from the biogas plant would account for about 5.5% of the energy consumption of the cattle and pig slaughter meat industry.

However, it is unlikely that all by-products from cattle and pig slaughter (post-flotation waste) will be managed in biogas plants, where the resulting biogas from fermentation processes would allow electricity to be produced. It would be a success if, in the next 2–3 years, at least half of such animal by-products were managed in this way. On the scale of the entire energy intensity of the meat industry, the electricity obtained would account for 2–3% of the energy consumed. It may seem that these are very small figures, but in specific companies, such shares can already be significant. Moreover, such a solution applied on a larger scale would reduce the so-called environmentally harmful carbon footprint. In addition, the resulting digestate, as a valuable organic fertilizer, could go to agricultural land and increase the revenues of meat companies. The advantage of biogas plant digestate is that it is easier to store compared to manure or slurry, since this product no longer ferments and has lower gas emissions, unlike the starting material. In addition, digestate used as fertilizer does not have such onerous term restrictions as manure. It should also be noted that animal by-products are essentially a free substrate for biogas plants, since when purchasing slaughter animals, the company, when paying for live weight, applies so-called deductions for the feeding of 3–4% for pigs and 6–8% for cattle.

A biogas plant can be a very effective way for meat companies to seek savings, especially with rising electricity and heat prices. The higher the prices for purchasing electricity on the market from power companies, the more profitable it becomes to produce energy from your biogas plant. In addition, taking into account subsidies for the construction of biogas plants for food companies (regardless of their size—small, medium, or large), the payback period for this type of investment will be shortened. Among other things, agricultural biogas plants can benefit from financial support from public funds.

In summary, it should be said that an increase in electricity prices, favorable legislation, and financial support for investment in biogas plants can support the development of such investments. From an economic point of view, for the rationality of such a project, the scale of the slaughter in plants is important, as it is crucial for ensuring the continuous supply of the required amount of substrate to the biogas plant. Therefore, the management of slaughterhouse waste, i.e., the content of the digestive tracts of slaughtered animals (cattle and pigs) in biogas plants is particularly advisable in medium and large slaughterhouses due to the scale of the waste obtained.

### *4.4. Examples of Companies Applying the Closed-Loop Economy in the Meat Industry*

A good example of a closed-loop economy is the Goodvalley agri-food company located in the Wielkopolska province. The indicated entity conducts integrated crop and livestock production and meat processing. It has 12,000 hectares of agricultural land (mainly arable land) and a feed plant, which provides properly balanced feed for pigs. At the meat processing plant in Przechlewo, some 700,000 pigs are slaughtered annually.

Eight biogas plants are an integral part of this enterprise's circular economy, which covers 100% of its electricity demand and about 70% of its thermal energy demand, with the surplus sold to the local grid. The substrates for biogas production are plant biomass,

animal excrement (manure), and some of the slaughterhouse waste (the contents of the digestive tract of slaughtered pigs), which undergoes thermal treatment [76].

The feedstock inputs of one of the 946 kW biogas plants in use at the Goodvalley agri-food company are as follows:

- slurry—55 tons/day;
- corn silage—35 tons/day;
- post-slaughter waste—3 tons/day.

Such substrates allow for the production of 6700 $m^3$ of biogas per day, which provides an annual electricity production of about 7100 MW. In addition, the resulting fermented sludge, as a result of the fermentation processes taking place, is a valuable organic fertilizer with a high nitrogen content. Its use on agricultural land contributes to reducing the carbon footprint. This model of Goodvalley's operation has been in place for many years and is constantly being improved [77].

Another way of managing animal by-products was implemented by Cedrob SA., one of the leading meat producers and processors in Poland. This enterprise has invested in a plant with a rendering profile. At the beginning of March 2020, the largest plant of this type in Poland and the most modern in Europe was put into operation. Within an area of 12,000 $m^2$ there were four processing lines, which deal with the processing of selected poultry raw materials sent by pipelines directly from the slaughterhouse. Each of the four production lines can be a separate specialized plant. Thanks to the close proximity of the slaughterhouse, the processed raw material is exceptionally fresh, which directly translates into the high quality of the products offered [68]. In addition, truck transport is not used to move animal by-products, which contributes to environmental protection.

It is possible that other smaller and larger meat processing plants will adopt similar solutions, thus introducing or developing a closed-loop economy, especially since Poland has the potential to increase milk, beef, poultry, and pork production. The pace and direction of these changes will be determined by the external environment, which consists of many factors including economic, legal, and administrative factors and international trade agreements. Issues related to ensuring health safety in animal production in connection with epidemiological or sanitary threats (e.g., ASF in pigs or avian influenza in birds) will also play an important role. It should also be borne in mind that some organizations are calling for the cessation of meat production and encouraging a reduction in meat consumption.

Any increase in animal production would automatically increase the weight of animal by-products, including those in Category 3, the sale of which meat plants have no problem with. Such by-products represent additional revenue for them from their sales. In addition, if an in-house pet-food plant is established, the transportation by truck of animal by-products to other entities is eliminated.

## 5. Discussion

The closed-loop economy in the meat industry, as in other sectors of the food industry, can be considered in the context of improving production efficiency in enterprises through the purposeful and rational use of animal or plant by-products generated in the production process. It can be hypothesized that food industry sectors that produce large amounts of by-products are preferable for the implementation and development of a closed-loop economy. One such candidate is the meat industry, in which, only from the slaughter of cattle and pigs, about 435 thousand tons of digestive tract content can be obtained.

As a result of the increasing consumption and production of meat, the slaughter and rendering industry has a growing production of inedible animal by-products. These products have a high nutritional value and can, therefore, be used to produce products such as fertilizers, feed, biofuels, and cosmetics. Animal fat can also be used to create alternative energy sources such as biodiesel and renewable fuels. In the EU, more than 20 million tons of animal by-products are produced each year in slaughterhouses, the food industry, and farms [78].

Animal by-products from slaughterhouses include various components of the animal's body, including blood, fat, and digestive tract content. Usually processed in energy-intensive processes such as rendering or the incineration of carcasses, they are an attractive substrate for biogas production due to their high organic matter content. Anaerobic digestion is a well-known biological degradation process [79] and can help to solve the problem of high energy consumption in meat processing plants. However, only animal by-products of Categories 2 and 3 (i.e., manure, digestive tract content, blood and carcasses, and the internal organs of healthy slaughtered animals) can be subjected to the biogas production process, always in combination with particle size reduction and appropriate special sanitary procedures such as pressure sterilization or pasteurization [63].

The use of animal products in biogas plants in Poland is limited by the small scale of production in most meat enterprises. According to unpublished data from the Central Statistical Office, there were 967 meat enterprises in the country in 2022. Their structure was dominated by small businesses employing up to 50 people, which accounted for 71.8%. The share of medium-sized enterprises was 21.6%, and large enterprises employing over 250 people made up only 6.6% of all meat enterprises. The profitability of biogas plants depends on the scale of production. Higher efficiency requires an appropriate amount of substrates, which can only be provided by medium and large meat enterprises.

The role and importance of biogas plants in the agri-food sector is highlighted by former Minister of Agriculture and Rural Development Marek Sawicki, who pointed out that faster development of biogas plants on agricultural land can make Polish agriculture zero-emission in a short time. In this regard, it is important to note that for small biogas plants, i.e., up to 500 kW, no building permit or environmental permit is needed, so they can be built overnight. Calculations made by J. Dach, among others, show that only 7 thousand biogas plants of average power up to 300 kW are capable of producing 21 TWh (terawatt hour) of heat and 21 TWh of electricity. In this situation, about 14,000 livestock farms could produce about 42 TWh or almost 1/3 of the energy needed from the substrate that is currently wasted [80]. This is important in the context of achieving zero carbon in food production, whether this will be a mandatory requirement or a desired state achieved voluntarily. Such biogas plants can also operate at processing plants that produce animal or plant by-products, given that the economic calculus supports this.

The Ministry of Agriculture and Rural Development is prioritizing the construction and development of biogas plants in rural areas. During a conference entitled "Fields of Power", which took place on 20 June 2024 in Gniewo, Michal Kołodziejczak, Deputy Minister at the Ministry of Agriculture and Rural Development, stated, among other things, that according to him, agricultural biogas plants are crucial for the Polish countryside, while stressing that energy production cannot be at the expense of reducing food production. In general, food production and energy production can complement each other perfectly. The weak link in the faster development of biogas plants is the difficulty of establishing energy connections and integrating them into power grids [81]. The effectiveness of energy production from animal by-products was pointed out by Wiesgickl, Weger, Jung, and Stenzel. In their opinion, a good solution is to use pressure-thermal hydrolysis in combination with anaerobic digestion. Pre-processing guarantees the complete sterilization of even highly infectious contaminated materials. In addition, recovering phosphorus from slaughterhouse waste can also be a sustainable solution for global phosphorus management [82].

However, building a biogas plant is expensive. According to information provided by an employee of Biogaz System S.A., it costs about PLN 16 million to build a 0.5 MW facility. The payback time of the investment varies, as it is based on market conditions, and can range from two to several years. In this situation, the decision to build a biogas plant requires a detailed economic calculation.

Given the amount of plant and animal by-products that are generated by food industry enterprises, it is more advisable to support the construction of biogas plants than to subsidize coal mining. It remains an open question who the beneficiaries of this kind of state aid would be.

The move toward climate neutrality in Europe is forcing the abandonment of fossil fuels and the introduction of legal solutions that promote a "closed-loop economy". This situation generates a number of both technical and social challenges. Local biogas plants make it possible to manage organic waste and convert it to digestate, which works very well as a fertilizer, and to useful electricity and heat. A biogas plant giving electricity to the grid can become an important element of a closed-loop economy and decentralized energy production system [83]. An important advantage of energy production from biogas is its independence from fluctuations in the price of energy resources, which are imported, among other things. This was particularly evident after the outbreak of the war in Ukraine, which caused a large increase in electricity and gas prices on world markets.

Zero-carbon food producers are more positively perceived by consumer markets, and thus are more competitive. According to Sawicki, there is economic sabotage in the Polish market perpetrated by energy companies who are hindering the development of renewable energy and biomethane production [80]. Meat companies, on the other hand, depend on farms with livestock production as their raw material base. An important issue in the future will be the assessment of creditworthiness and the level of cost of loans to food industry enterprises, including meat enterprises, by financial institutions. When considering applications, the level of emissivity of greenhouse gases, mainly $CO_2$, in enterprises will be taken into account for the suppliers and producers of slaughter livestock. Relatively high levels of greenhouse gas emissions into the atmosphere, and a lack of measures taken to reduce them, will mean a higher cost of credit, or even denial of credit.

Due to the high energy intensity of the food industry, including the meat industry, energy prices are crucial to their operation. In Poland, wholesale energy prices are among the highest in Europe. This negatively affects the Polish industry and reflects on the economy as a whole, as companies become less competitive. According to Polityka Insight, after the first seven months of 2024, the average wholesale price of electricity in Poland was €90 per MWh. Higher prices during the period were recorded only in Ireland (€98.68 per MWh) and Italy (€95–98 per MWh). In contrast, the lowest energy prices were in the Scandinavian countries of Norway and Sweden, where they stood at €32–39 per MWh. As R. Tomaszewski explains, in those countries where there is a so-called energy mix based on renewable energy sources and energy from nuclear power plants, electricity prices for households and industry are the lowest [84]. This type of situation does not exist in Poland, where electricity production is based on coal.

To develop the concept of a closed-loop economy, in mid-2024, the Polish Agency for Enterprise Development (PARP) announced the launch of a call for applications for the second stage of the "Closed-loop economy in SMEs" program financed by the European Funds for Eastern Poland 2021–2027 (FEPW). This program is aimed at micro, small, and medium-sized enterprises in the Eastern Poland region. The action taken focuses on implementing advanced closed-loop economy business models—energy system transformation [85].

Support for the construction of biogas plants can also be obtained from a program entitled "Cogeneration for Energy and Industry", aimed at entrepreneurs. The application deadline is from 22 April 2024 to 19 December 2025, or until the allocation of funds is exhausted. The program applies to, among other things, the construction or reconstruction of biogas plants. Support in the program is to be provided by a grant, which in the case of biogas plants will range from 45% to 65%. The subsidy is conditional on taking out a loan from the National Fund for Environmental Protection and Water Management.

A 2023 study on the potential of the circular economy, commissioned by Stean Recycling and involving a group of 400 companies, shows that Polish entrepreneurs' activities in the area of the closed-loop economy are very limited. More than 78.7% of the surveyed entities generate recyclable waste, but only 37% apply solutions related to the idea of the circular economy. Financial support from PARP in this area can amount to as much as PLN 3.5 million for one enterprise [86].

## 6. Conclusions and Recommendations

Reducing waste production and reusing and recycling waste are important parts of a closed-cycle economy. In meat companies, waste from slaughtering animals can be properly managed, either by processing it into animal feed or by using it in biogas plants to generate electricity or heat. Educating meat producers about the harmful effects of inadequate waste disposal is key in this regard. Various organizations should take active steps to raise awareness among meat entrepreneurs about waste treatment. Their efficient use will not only protect the environment but also benefit the economy by extending the life cycle of the product. In this way, a closed-loop economy will be promoted. Such activities will also increase the income of entrepreneurs and farmers.

The food industry needs to adopt the concept of a closed-loop economy to create a closed system that effectively manages food waste in production, distribution, and consumption. A closed-loop economy in meat enterprises can yield tangible benefits and savings, especially since the meat industry consumes the most energy of all food industries.

A limitation of the study is the limited access to data on the amount of waste generated and its use in a closed-loop economy. This study analyzes the volume of production and ways of managing animal by-products for only one country—Poland. In subsequent studies, it would be advisable to conduct research in other countries of the European Union and compare the methods of management and efficiency of use of this type of waste in different economies.

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