

Review

Sugar Beet Pulp in the Context of Developing the Concept of Circular Bioeconomy

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Abstract: The primary objective of this paper is to identify the possibilities of using sugar beet pulp as feedstock to produce a variety of added-value products. Such an application of the sugar production byproducts contributes to implementing circular bio-economy, which is a source of many economic, social, and environmental benefits. Specific objectives of this paper are: (1) Presenting the concept and meaning of circular bio-economy. (2) Characterizing properties of the sugar beet pulp from the perspective of using them as feedstock. (3) Determining the volume of production of the sugar beet pulp and the current methods of using them. (4) Determining the methods of obtaining attractive bioproducts and renewable energy from sugar beet pulp. Special attention was given to the amount of sugar beet pulp produced in Polish sugar refineries. Poland is among the European countries in which the volume of produced sugar is especially high. Therefore, the problem of appropriate waste management in the Polish sugar industry gains significant importance. The conducted literature review demonstrated that sugar beet pulp might be used as a feedstock in the production of many bio-products produced using a variety of methods.

Keywords: circular economy; bioeconomy; sugar beet pulp; biogas; bioproduct; ethanol



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1. Introduction

The solutions representative of the circular economy (CE) concept took on special importance in the XXI century. One of the complete lists based on a comprehensive analysis of “circular economy” definitions was made by Kirchherr et al. [1]. They compiled 114 circular economy definitions, which were coded on 17 dimensions referring to the principles, goals and factors enabling the implementation of the assumptions of CE. Kirchherr et al. (2016) looking for the definition of CE for analyzes and compilations, adopted a holistic view and comprehensively used by Ghisellini et al. [2].

Combining the review made by Kirchherr et al. [1] with other mapping and analysis of CE approaches made by Linder et al. [3] it can be indicated that: The XXI century brought an approach to CE through the prism of industrial ecology, including cradle-to-cradle design and biomimicry. It also draws upon Boulding's concept of “Spaceship Earth”; Daly's “steady-state economy”, and Stahel and Reday's “loop economy”. These ideas were approved by policymaking spheres within the European Union (EU), China, and Japan and have been popularized by think tanks and non-governmental organizations such as the Green Alliance and the Ellen MacArthur Foundation. The ultimate goal of a circular economy is sustainable development.

In most countries, the approach to CE is dominant through the prism of the environmental and economic dimensions. The exception is the Asian economies of the Pacific region, where the CE interpretation covers social factors within the broader political goal of a more “harmonious society” [3].

Whereas some definitions include the concepts of economic value and reduced energy consumption, the essence of a circular economy is related to the introduction of closed-loop product, resource, and material cycles as a means to improve resource efficiency. Several definitions of the circular economy focus on closed-loop cycles: “A self-sufficient economic regime conducted through ‘closed loops’ of materials”; “A closed cycle of material and energy flows”; “The core of CE is the circular (closed) flow of materials”; “A CE is an industrial system focused on closing the loop for material and energy flows”; “In a circular economy, resources are kept in use for as long as possible, extracting their maximum value”; An economy “... in which the conceptual logic for value creation is based on utilizing economic value retained in products after use”; “CE... aims at reducing both input of virgin materials and output of wastes by closing economic and ecological loops of resource flows”; An economy “... where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimized” [3].

Definitions published in reports prepared for practice should be considered as correlating with the approach according to which the circular economy is defined as an economic system based on the possibility of re-using products and their components, recycling materials and protecting natural resources while striving to create added value in every link of the system [4].

Such an approach unequivocally poses a challenge for entities of the micro- and macroeconomic scale in the form of taking actions promoting a better closing of product and material chains.

Circular economy is most frequently depicted as a combination of reduce, re-use and recycle activities, whereas it is frequently not highlighted that CE necessitates a systemic shift. The definitions show few explicit linkages of the circular economy concept to sustainable development. The circular economy is considered to be economic prosperity, followed by environmental quality; its impact on social equity and future generations is barely mentioned. Furthermore, neither business models nor consumers are frequently outlined as enablers of the circular economy.

The attention should also be paid to the definition of CE, formulated by Kirchherr et al. [1], who presenting CE through a prism, an economic system that replaces the “end-of-life” concept with reducing, alternatively re-using, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), intending to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. What is more, novel business models and responsible consumers enable it.

The essence of the circular economy understood today is also reflected in the approach according to which “a circular economy” can be defined as an economic model aimed at the efficient use of resources through waste minimization, long-term value retention, reduction of primary resources, and closed loops of products, product parts, and materials within the boundaries of environmental protection and socio-economic benefits. A CE has the potential to lead to sustainable development while decoupling economic growth from the negative consequences of resource depletion and environmental degradation [5].

The circular economy is oriented towards keeping the products, materials, and feedstocks in the economy for as long as it is possible while simultaneously minimizing the volume of wastes, which are also treated as secondary raw materials.

Circular economy using waste to produce new goods is an alternative to the traditional, unsustainable linear economy, often dependent on available fossil resources [6–8]. Moving from a linear economy model to a circular economy model requires more renewable

biological resources, including bio-waste [9]. Such an approach, known as bioeconomy or circular bioeconomy, may, at least partially, replace the traditional way of producing certain goods and energy and underpin the global economy [10,11]. The bioeconomy with its potential ecological, social and economic benefits is thus becoming a “global concept” of interest to various countries and various public and private entities [12,13].

The circular economy, which correlated with the term bioeconomy is based on the Ellen MacArthur Foundation diagram [14] and technical cycle, which encompasses non-renewable resources as well as biological cycle referring to renewable resources (biomass) and to the activities, which exhibit circularity.

Bioeconomy is one of the key pillars enabling to implement and execute the close-circuit activities, oriented towards not only extending the products life-cycle but also on maintaining the high quality of feedstocks in the entire life-cycle of the bioproduct (from sourcing, through production, storage, transportation, consumption, to waste disposal).

The conversion of biomass into marketable products relies on the accessibility and quality of renewable feedstocks [15,16]. Environmental limitations of the bioeconomy development include in particular, the seasonality of supplies, the geographic distribution of resources and competition for the available land [8,17,18]. Economic factors affecting the bioeconomy are production and transportation costs, resources prices, and resulting products [19]. Many other factors influence bioeconomy development, such as scientific advances, innovative activities, availability of funding sources, consumer preferences, public acceptance for genetic technologies, and even fiscal policies [15,20].

The primary objective of the paper is to present the benefits and uses of the sugar beet pulp, a byproduct of producing sugar from sugar beets, in the context of developing the concept of circular bioeconomy. Special attention was given to the volume of the beet pulp produced in Polish sugar refineries and the current use of such bio-waste. Poland is one of the European countries, which produces exceptionally high amounts of sugar [21]. According to the European Association of Sugar Manufacturers, during the 2018–2019 sugar campaign, 2.2 million tonnes of sugar were produced in Poland. It constituted about 13% of the total sugar production in the European Union. Poland ranked third in sugar production in the UE (after France and Germany) [22]. In Poland, all sugar is produced from sugar beets [23]. Therefore, the problem of proper management of waste from the Polish sugar industry becomes especially vital.

Specific objectives of this paper are:

- Presenting the concept and meaning of circular bio-economy.
- Characterizing properties of the sugar beet pulp from the perspective of using them as feedstock.
- Determining the volume of production of the sugar beet pulp and the current methods of using them.
- Determining the methods of obtaining attractive bioproducts and renewable energy from sugar beet pulp.

Theoretical considerations were based on the analysis of source literature and the legal acts pertaining to the circular economy and bio-economy.

2. Circular Bioeconomy—The Concept and Meaning

The linear economy model is highly dependent on fossil-based resources used as feedstock. Raw material inputs, byproducts, and products used in production and consumption processes finally become waste, which is not reused or recycled. The consequences of such unsustainable industrial system include depletion of non-renewable resources and large amounts of waste being landfilled [8,24].

The linear model has to be replaced with a more efficient circular economy to develop more sustainable production systems. The circular economy aims to promote resource efficiency and reduce waste generation as waste streams are used as inputs for production processes [6]. In some cases, waste can be converted into high-value products [10].

The circular economy is the type of economy, which aims at minimizing the time, space, matter, and energy (including feedstock and waste), while at the same time maximizing the efficiency of their use by creating closed process loops.

Process loops in the circular economy are based on the Ellen MacArthur Foundation diagram and refer to two cycles (more on this subject in lines: [25,26]):

- (1) Technical cycle, encompassing non-renewable resources, meaning the resources that cannot be renewed as a result of natural processes, or it will take a very long time to do so.
- (2) Biological cycle, encompassing renewable resources meaning the resources that can be renewed on an ongoing basis, or the renewal happens very fast. The biological cycle also refers to:
 - The biomass, that is the part of the product, waste, residues, which are biodegradable;
 - Residues of biological origin;
 - Industrial biomass.

The Ellen MacArthur Foundation diagram presents the above issues [14]. Based on the diagram already mentioned [25,26] there are three basic assumptions of the circular economy:

- (1) Preserving natural capital by balancing natural resource flows (loops of natural resource cycles).
- (2) Optimizing the use of raw materials by maintaining finished products and components for their production in the cycles mentioned above (technical and biological).
- (3) The continuity of increasing the efficiency of the circular economy system through the constant identification, monitoring and removal of negative external consequences associated with flows of flows.

Because the circular approach to the economy assumes the need to secure waste so that it can re-enter the biosphere, and non-biological materials can be processed in a way that is not harmful to the environment, it is possible to eliminate waste and retain the value of products/resources as long as possible.

In the model of the circular economy, wastes from one process are used as a starting feedstock used for conducting other processes, which, in consequence, reduces the amount of production waste.

According to the above considerations, the circular economy model is the opposite of the linear economy model. In the linear model, materials are not re-used or recycled [24]. In other words, material loops are not closed, which leads to the increase of waste being disposed into landfills. A key characteristic of developing the circular economy model is what also makes it different from the linear economy model that is circularity. In this model, the added value of resources, materials, and products is maximized while the amount of waste is minimized. The wastes are re-used, in compliance with the effective procedure and hierarchy of dealing with waste and byproducts.

In order to implement circular economy principles, it is essential to develop conversion technologies using various biomass feedstocks to produce biobased products, energy and chemicals [16,27–30]. This also involves using waste biomass such as agro-industrial wastes, municipal wastes or industrial byproducts and transformation into valuable products [29,31]. Biobased products and energy generated using biomass include for example, food, chemicals, materials, cosmetics, and biofuels [18,28,32].

Waste bioconversion does not require agricultural land and helps to save energy and water and hence it has the potential to be cost-effective [33]. Other potential benefits include reduced synthetic chemicals and lower environmental pollution [34,35]. Several thermochemical and biochemical methods can convert residues into valuable products [36]. These include fermentation, anaerobic digestion and gasification [36].

The transformation of the linear economy model into the circular economy model implies many benefits compared in Table 1.

Table 1. Linear economy vs. circular economy.

Effects of the Linear Economy	Effects of the Circular Economy
<ul style="list-style-type: none"> • Execution of the developmental model oriented towards reaching economic goals while at the same time not taking into account the social and environmental limitations or ignoring them altogether • High dependence on natural resources, especially fossil resources • An increase in the cost of producing scarce natural resources and an increase in the cost of these resources • Permanently limiting the access of business entities and consumers to these resources. • Shortening the product life cycle while simultaneously maximizing the production of waste and degradation of the environment • Increase in the chains and networks of deliveries of the amounts of irretrievably lost materials. • Increase in the amount of waste subject to landfilling; wastes are not considered usable materials • The growing environmental footprint related to the negative influence of human activity on the biosphere and atmosphere 	<ul style="list-style-type: none"> • Reduction of consumption and protection of natural resources as well as their more efficient use • Reducing the amount of waste subject to landfilling, among others thanks to the re-use of products, the use of waste (including bio-waste) in the production processes of products with added value • Less use of toxic chemicals • Development of eco-innovations • Increase in GDP as a result of combining the increase in revenue related to new circular activities and cheaper production obtained inter alia by identifying new applications and usability • Increase in the number of workplaces requiring knowledge, qualifications, and abilities, which refer to inter alia recycling, environmental protection, closing the physical flow loop in chains and networks of deliveries, biotechnology, bioengineering, monitoring and identifying of new applications of products to extend their life-cycle • Reduction of the CO₂ emission and slowing down the depletion of natural resources • Reduction of ecological, social and economic problems • Execution of the developmental model based on the concept of sustainable development

Source: own elaboration based on [6–9,14,16,24,30,34,37–41].

The unquestionable consequence of closing the loop of the economy is the possibility of economic growth by simultaneously minimizing the depletion of resources, matter, and energy. In other words, by re-using and recycling materials, the circular economy model can contribute to decoupling economic growth from the use of natural resources [42]. However, it should be noted that some authors are skeptical about the possibility for “sufficient decoupling” [42].

According to information included in Table 1, the model based on the exploitation of exhaustible non-renewable resources leads not only to the high amounts of waste but also to many other environmental, economic, and social problems. These include increasing greenhouse gas emissions resulting from the use of fossil fuels, reducing resource dependency, and fluctuations of oil prices [43]. In order to tackle the challenges posed by sustainability, one can address them by switching to an economy based on renewable biological resources, which are generated and converted into other value-added bio-based products, including energy products [44]. This issue is related to the term already mentioned in the introduction section, namely bioeconomy.

It is believed that the concept of bioeconomy was introduced by J. Enriquez [16,45]; however, in his article he did not use this term [46,47]. The term “bioeconomy” was previously used to describe the use of biological knowledge for commercial and industrial applications [12,47]. Currently, the “bioeconomy” is understood quite differently in the literature and strategic documents [48]. Bioeconomy is treated as a world [49], an economy [50], an approach [44] or “the global industrial transition” [51] using processes such as production, conversion, utilization and conservation of renewable bioresources [44,51–53]. Therefore, biotechnology is used on a large scale in the bioeconomy [49], allowing the production of various goods and energy [44,51,52]. Innovation, knowledge and research [48,54] are of great importance here. Goods (e.g., food, drugs) produced, at least in part from renewable biological resources and biowaste streams, are expected to bring economic, social, and environmental benefits [9,10,44,51,52,54]. Table 2 presents a division of potential benefits. The benefits are a result of implementing the solutions, which refer to bio-economy. When creating the compilation of the benefits, a decision was made to divide the benefits

into three sub-categories: economic, social, and environmental. However, in terms of sustainability impact, the bioeconomy impact assessment is ambiguous. It is indicated that this impact may be beneficial only under certain conditions, and in some cases—even negative [55]. Concerns concern, inter alia, that “nonfood” biomass production competes with food production for land and may be a source of large carbon dioxide emissions due to land-use change [50,55].

Table 2. Potential benefits of bio-economy.

Economic Benefits	Social Benefits	Environmental Benefits
<ul style="list-style-type: none"> • New investments, economic growth, and contribution to local development • Development of new markets • Innovations • Reduction of production costs • Production of a variety of products from one biomass source • Satisfying investors’ demand for sustainable production processes • Minimization of the volatility of oil prices and its influence on business cost and investment decision • Improved cooperation along regional value chains 	<ul style="list-style-type: none"> • Creation of new jobs, especially in rural areas • Additional sources of revenue for farmers and biorefineries • Improvement of the quality of life of farmers and employees of biorefineries • Food security 	<ul style="list-style-type: none"> • Reduction of the use of fossil resource and dependence on scarce resources • Minimization of generated landfills and waste, sustainable waste management • Reduction of greenhouse gas emissions, • Recycling of nutrients • Reduced use of oil and synthetic chemicals • Enhanced environmental awareness

Source: own elaboration based on: [6,7,18,19,34,43,44,56–61].

Bioeconomy or sustainable bioeconomy used to be initially considered to be an integral component of the circular economy model [16,18,57,62]. Bioeconomy is also seen as circular through its inherent nature or as a model, which is just in agreement with the circular economy approach [18,24].

Recently researchers developed the concept of circular bioeconomy, which relies on sustainable and resource-efficient use of different biomass feedstock, including waste [18]. Some authors consider circular bioeconomy the intersection of the two concepts (mentioned above): bioeconomy and circular economy [11]. However, circular bioeconomy is also considered to be something more than those two models alone [18].

The concept of circular bioeconomy involves the use of biorefineries. The biorefineries use renewable bioresources, including agro-waste and byproducts, to produce energy (biofuels, electricity, heat) and a variety of products such as food, animal feed, materials, and chemicals, including pharmaceuticals [16,18]. Such facilities can utilize a variety of biological resources, including:

- Lignocelluloses,
- Algae (microalgae),
- Agricultural, municipal, industrial, and forest waste and residues such as, for example, manure, food, sludge [16].

Comprehensive, multi-platform and simultaneous processing of large amounts of waste biomass and agro-industrial wastes to chemicals, energy and fuels should take place in biorefineries. On the other hand, low-tonnage conversion should take place in possibly waste-free processing plants: local, in-house, rural, automated, and characterized by simple operation and easy operation, operating as container and portable installations, located near the places where waste is generated. For example, the location of a processing plant processing beet pulp should be located in the vicinity of a sugar factory, which would significantly shorten the transport route of the raw material and reduce the costs of its processing. Both in-house and rural processing plants could produce a small amount of a few chemicals of high commercial value, increasing the profitability of production,

and produce large amounts of less valuable low-cost products for feed, fuel, and energy, used for personal use or for sale. Also, the most valuable products obtained under these conditions could be sent for further processing and refinement in biorefineries, which process lignocellulosic, protein and fat biomass in an integrated manner on a large scale.

Bioresources can be both locally sourced or imported. In biorefineries, different conversion technologies can be applied, namely thermochemical, biological, chemical (biochemical), and mechanical [16].

The biomass can be converted into high amounts of relatively low-priced products such as animal feed [63]. Available technologies can also be used to convert different feedstock into more valuable products [34]. From the perspective of the economic pillar of sustainable development, it would be desirable to maximize the added-value and fully utilize the chemical potential of renewable resources [19,64].

Biorefineries face many challenges. Some of these challenges are technological and result from the fact that technologies have not yet been sufficiently developed and matured (e.g., production of chemicals) [65,66]. There is also a certain degree of uncertainty when it comes to the results of virtual production processes as some processes or research have been performed in laboratories [10].

Table 3 presents a summary of limitations, which inhibit and sometimes prevent from implementing the premises of the concept of circular bioeconomy.

Table 3. Limitations of implementing the premises of circular bioeconomy.

Nature of Barriers and Limitations	Examples
Market	<ul style="list-style-type: none"> • Land competition between bioenergy and food and its impact on food prices • Relatively high or uncertain costs of starting and running biorefineries and producing products (these may be probably minimized when integrated with existing plants) • Costs of renewable feedstock • Costs of technology, including energy costs • Competition with traditional, developed markets and deep-rooted value chains which can increase the costs of production (in comparison to current value chains) • Low market share of bioproducts • Seasonality of biomass supply, which leads to production downtime • High transportation costs due to the low density and geographical diversity of feedstock
Regulatory	<ul style="list-style-type: none"> • The uncertainty about renewable policy, regulations, and financial support for research and production • Cooperation between different parties: private businesses, authorities, and research centers
Technological	<ul style="list-style-type: none"> • Immature technologies
Cultural	<ul style="list-style-type: none"> • Traditional business models based on linear processes • Insufficient governmental policy and support
Environmental	<ul style="list-style-type: none"> • Negative environmental impact due to the increase in agricultural production (emissions from machinery used in farming, eutrophication and other effects of fertilizers, biodiversity losses, the environmental impact of pesticides and herbicide) • Environmental impacts of biorefinery facilities (air and water pollution) • Relatively high levels of greenhouse gas emissions from certain biofuels across their life cycle • Impact of climate change on some regions and businesses operating there

Source: own elaboration based on: [8–10,16–19,34,59,60,65,67–71].

3. Production of Sugar Beet Pulp

Sugar beet pulp is the main byproduct of producing sugar from sugar beets [66]. It is a sugar-depleted material left after extracting sucrose from sliced beetroots [72,73].

The pulp, which is created in the course of processing the sugar beets, is known as wet or fresh pulp. Dry matter concentration in the wet pulp amounts to about 6–12% [74]. According to the Commission Regulation (EU) No 68/2013 of 16 January 2013 on the Catalogue of feed materials, the minimum moisture content in wet sugar beet pulp amounts to 82% [75]. The wet pulp is susceptible to spoilage, hard to store, and costly in transportation [74,76,77].

Beet pulp may be pressed to reduce the moisture content. As a result of the mechanical squeezing of water, dry mass content in pressed pulp increases to 18–30% [74,76,77]. To prevent spoilage the fresh-pressed pulp should be used within a few days [74]. It is rarely sold to local farmers, who ensile it for animal feeding [78,79].

Pressed beet pulp is often dried and processed into pellets before being packaged to be sold as animal feed. Dehydrating and pelletizing are relatively energy-intensive processes, which constitute 30–40% of the total energy cost of beet processing [80]. The concentration of dry matter in the dried pulp amounts to about 87–92% [74]. In some cases, beet pulp is mixed with molasses to increase the energy content and improve its palatability and nutrient value of the beet pulp used as feed [81,82].

Sugar beet pulp is composed mainly of polysaccharides, such as pectin (18–30% w/w on a dry weight basis), cellulose (19–27%), and hemicellulose (20%–36%) [83,84]. It also contains lignin but in much lower proportions. Sugar beet pulp also includes protein (7–15%) and minor fractions of fat and ash [56,82,84,85].

According to the FAO data, in the years 2014–2019, annual global sugar beet production totaled at 241–314 million tonnes. In Poland, sugar beet crops reached 13.8 million tonnes and constituted 5.0% of the global crops in 2019 [86]. According to the CEFS, during the 2018–2019 sugar campaign, 2.2 million tonnes of sugar were produced in Poland. It constituted about 13% of the total sugar production in the European Union. Poland ranked third in the sugar production in the UE (after France and Germany) [22]. In Poland, all sugar is produced from sugar beets [23].

About 6.6 tonnes of sugar beets are required to produce 1 tonne of sugar [87]. For each tonne of the sugar beets being processed, respectively, about 160–500 kg and 51–70 kg of wet or pressed pulp and dried pulp are produced [88–90]. Accurate values depend on sugar beet cultivar, growing conditions of the crop, and processing of beetroots in sugar refineries [90].

According to the CEFS, in the 2015–2016 sugar campaign, approximately 10.4 million tonnes of fresh sugar beet pulp was generated in the European Union. In Poland, the total amount of 3.6 million tonnes was produced [22]. A large amount of beet pulp produced in Poland is a consequence of relatively high sugar production [77]. The amounts of dried pulp produced in Poland were relatively small [22].

Figure 1 provides information on the production and sales of beet-pulp, bagasse, and other sugar manufacturing waste in Poland.

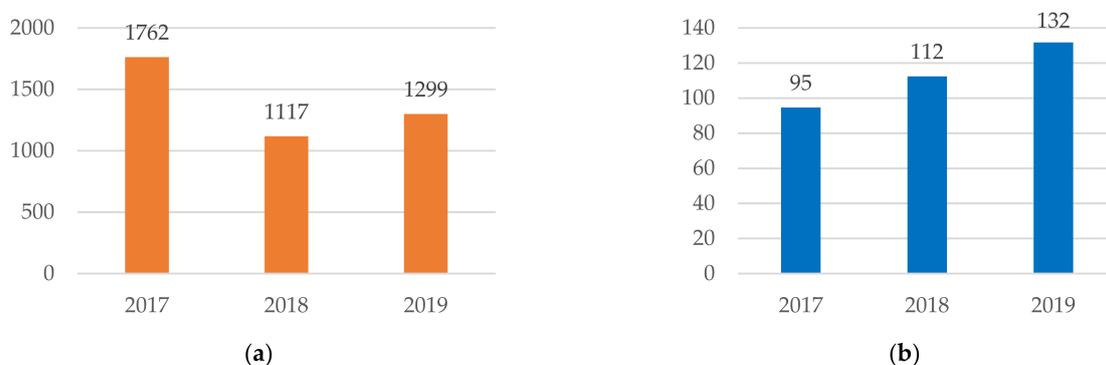


Figure 1. (a) Production sold (in thousand tonnes) of beet-pulp, bagasse and other waste of sugar manufacturing in Poland. (b) Production sold (million PLN) of beet-pulp, bagasse and other waste of sugar manufacturing in Poland. Own elaboration based on: [91–93].

4. Current Uses of Sugar Beet Pulp

Despite its high sugar content and substantial biorefinery potential, beet pulp is most often used as animal feed [67]. It is considered to be a valuable feed for livestock due to its high energy content [73,94]. In Poland, the market net price of sugar beet pulp amounts to about 1300 PLN per tonne [95]. Reasons for not using the pulp as animal feed are its quality or lack of animal farms nearby [96,97].

In Poland and some of the European countries, sugar beet pulp is used to produce biogas [98]. A biogas plant, which runs exclusively on beet pulp as raw material, is located in Strzelin (south-western Poland). Biogas is obtained through anaerobic digestion of wet or ensiled pulp. The plant operates all year round as it has a steady stream of supply. However, the wet pulp is utilized only during sugar campaigns [99].

Being a renewable energy source, beet pulp, and other sources of biomass help to tackle climate change and reduce greenhouse gas emissions and other pollutants from fossil fuel combustion. Biogas plants using pulp and other byproducts of the sugar industry could also be profitable investments [100].

The pulp, which was not used as an animal feed or feedstock intended for biorefinery facilities, could be dumped in landfills [96,97]. In situations when disposal of the pulp can be burdensome for the environment and for the society, which has to bear the cost of waste management, some economic benefits of sugar production are lost [101,102].

The volume of wastes generated in Poland, in the years 2011–2016, in the form of sugar beet pulp, is presented in Figure 2.

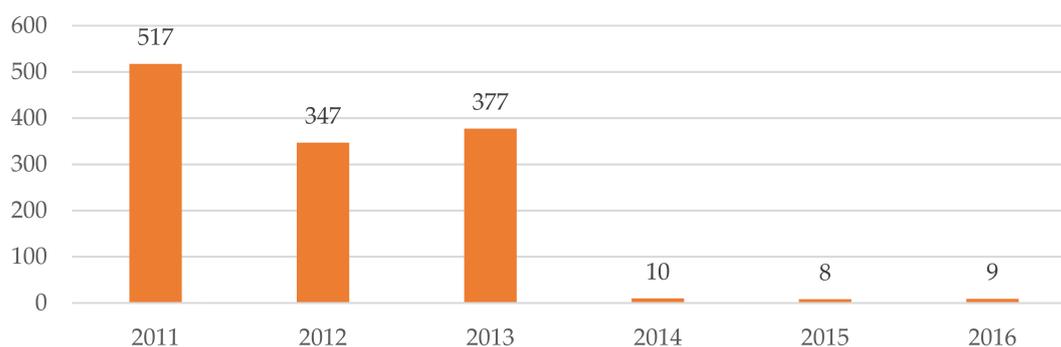


Figure 2. Amount of waste (in thousand tonnes) generated in Poland in the form of sugar beet pulp (more recent data is not available) Own elaboration based on: [103,104].

In Poland, landfilled waste is subject to a landfill charge. In 2011–2020 the rate of the charge levied on one tonne of sugar beet pulp as well as the other kinds of waste from the sugar industry was 11.32–13.13 PLN [105,106].

5. New Applications of Sugar Beet Pulp as an Example of Implementing the Circular Bioeconomy Concept

Sugar beet pulp is a sugar beet processing residue, which has a great potential as a component of bioeconomy because it can be converted into a variety of valuable products and byproducts. The pulp is produced in large amounts, it is low priced, widely underused, and has a suitable chemical composition [107–110]. The latter is related to many useful components, including high polysaccharides fraction [97,108,111,112]. However, it should be noted that sugar beet pulp composition may be different, depending, e.g., on weather conditions [113].

One way to produce value-added products from beet pulp is to convert it into bioethanol [80]. It could increase the economic viability of using sugar beet pulp in comparison to selling it as feed [80]. Potential benefits may result from lower energy costs as pulp used to produce biofuels does not need to be dried [80].

In order to obtain ethanol from sugar beet pulp Zheng, Y. et al. (2013) used simultaneous saccharification and fermentation [84]. The maximum ethanol yield obtained by Rezicó, T. et al. (2013) amounted to 0.1 g ethanol/g of dry weight [71].

Table 4 provides an overview of methods used to produce other bioproducts from sugar beet pulp.

Table 4. Processes used for obtaining valuable intermediates and bioproducts from sugar beet pulp.

Products	Extraction Method/Technology	Reference
Pectin	Different extraction procedures, including acid (HCl) extraction	[114]
Pectin	Microwave-assisted extraction	[68]
Galacturonic acid	Enzymatic release of galacturonic acid	[113]
L-arabinose	Few steps, including treatment with aqueous alkali	[115]
L-Arabinose and oligosaccharides	Xylanase and acid hydrolysis	[116]
L-arabinose and a galacturonic acid-rich backbone	Enzymatic hydrolysis of sugar beet pulp	[89]
Arabino-oligosaccharides	Hydrothermal treatment	[117]
Pectic oligosaccharides	Enzyme membrane reactor technology	[118]
Succinic acid	Fed-batch fermentations with the bacterial strain <i>Actinobacillus succinogenes</i>	[31]
Ferulic acid and feruloylated oligosaccharides	The release of products from sugar beet pulp was carried out with the actinomycete strains	[119]

Source: [31,68,89,90,113–119].

Sugar beet pulp along with apple pomace and citrus peel are considered “pectin-rich agro-industrial residues” [109]. Different types of residues and extraction procedures affect the properties of pectins [67]. A conventional and commonly used method for extracting pectin from beet pulp is the method using acid, but there are also other methods [120]. Unconventional methods of extraction may be expensive and not cost-competitive when compared to traditional acid methods [67].

Methods of extracting pectins from sugar beet pulp have an environmental impact [67] and the environmental conditions in sugar beet pulp processing procedures include, for example, proper treatment of utilized acids and bases [31]. There is also a problem with disposing of solid residues, which have no practical application yet [121].

Pectins are used primarily in the food industry. However, sugar beet pectin has some undesirable qualities compared to pectins extracted from other plants. That limits its commercial food applications [122]. Unlike pectins extracted from citrus peels or apple pomace, sugar beet pectin is not typically utilized as a gelling agent for jams and jellies [123]. The reason for that is its limited gelling ability due to a high degree of esterification and the presence of acetyl groups [66,124]. However, some successful applications of sugar beet pectin in the food industry have been indicated in the literature [123]. The emulsifying capacity of sugar beet pulp pectin is better compared to the capacity of pectin extracted from other sources [125]. Beet pectin can also be used as a thickening agent and to increase the viscosity of some types of food (e.g., ketchup) [126].

Pectin-extracted sugar beet pulp has been investigated as a bio-sorbent used for the removal of heavy metals (copper, lead, and cadmium) from aqueous solutions, including wastewater [127].

Pectins extracted from different plants can be also used in other non-food industries, such as cosmetic and pharmaceutical industries, for example, as drug carriers or binding agents in tablets [128].

Pectin-rich residues, including sugar beet pulp, show the potential to be processed into pectic oligosaccharides, which can be used as potential prebiotic compounds [118]. Pectic oligosaccharides are investigated for antibacterial potentials [118].

The environmental impact of the production of oligosaccharides from sugar beet pulp pectin was assessed by S. González-García et al. using the Life Cycle Assessment (LCA) [108]. The authors investigated both conventional autohydrolysis and the enzymatic hydrolysis.

The primary monosaccharides found in pectin, which were extracted from sugar beet pulp, include D-galacturonic acid, L-arabinose, and D-glucose [66]. Other sugars found in pectin isolated from sugar beet pulp include D-galactose, L-rhamnose, and D-xylose [34,66,129]. Some of those have a range of potential applications.

D-galacturonic acid (GalAc) is a building block of a variety of ingredients and products, used in food, pharmaceutical, and cosmetic industries [113]. L-arabinose, used as a starting raw material, is also known to have a wide range of applications in the food and pharmaceutical industries. It can be used to produce healthier food products in order to lower the glycemic index and blood glucose level [130].

The development of low-cost L-arabinose production technologies is driven by the increasing demand and searching for cheaper feedstock sources [116]. Alternative raw materials include not only sugar beet pulp but also agro-waste such as vegetable gums, corncob, or bagasse [131].

Arabinose can be used to produce L-gluco-heptulose, which is also of pharmaceutical interest [31,132]. It is also possible to produce arabinitol (polyol arabitol) by reducing L-arabinose [133]. Arabinitol is a sugar alcohol with a low-calorie content, which is used in the food industry as a sweetener [134]. It can also be used as an anti-cariogenic agent [135].

Hydrolysates of sugar beet pulp contain acetic acid [109]. The pulp can also be used to produce furfural, which can be processed into marketable products such as fuels, plastics, or solvents [74,136].

Sugar beet pectin contains ferulic acid. Potential applications of ferulic acid include protection of the skin against photooxidative damage or chemo- and radiotherapy [119,137].

Sugar beet pulp can be converted into succinic acid, which can be used as a precursor for the production of bio-renewable copolymers and chemicals [31,138]. The market price of 1 kg of the succinic acid is \$2.9 [31]. The market of succinic acid produced from renewable resources is promising as it grows very fast [31].

Cellulose is a useful component of the sugar beet pulp [81]. It can be converted into carboxymethyl cellulose using the etherification process [139]. This cellulose derivative has some applications in the food, cosmetic, and pharmaceutical industries. It can also be used in drilling mud and detergents [139,140]. According to R. Nolles and F. Staps, fibers from sugar beet pulp can be used in the paints and coatings industry [141].

Sugar beet pulp has also been used to obtain products such as:

- Biodegradable composites (thermoplastics) used as a lightweight construction material [142];
- Biocompatible material at high-temperature applications (made from cellulose nanofibers) [90,143];
- Paper used, e.g., for printing or photocopying [144,145]. Beet pulp can partially substitute wood fibers [85].

6. Energy

It should be noted, that according to the state of the art and knowledge regarding the further processing of sugar beet pulp, only these solutions are possible to implement on industrial scale, in which there is an excess of waste energy, both heat and electricity, which makes the described technologies and products obtained profitable, from the point of view of the circular economy philosophy.

The profitability of using beet pulp will be determined by many complex and often variable factors, e.g., the course and conditions of sugar beet cultivation, including the type

and amount of fertilizers used, weather parameters (insolation and precipitation), yield per 1 ha, distance between beet cultivation and sugar factories, beet storage conditions, sugar production technology, and finally adopted solutions in the field of processing of pulp.

Biorefining sugar beet pulp biomass for bioenergy production represents an opportunity for both sustainable energy supply and greenhouse gas emissions mitigation. In the work of D. Tonini et al. [146], to assess the importance of the alternative use of biomass residues (among others sugar beet pulp), a consequential LCA of many different energy-focused biorefinery scenarios was performed and a few conversion pathways (two involving bioethanol and two biogas). In this paper the authors a dedicated biochemical model developed to establish detailed mass, energy, and substance balances for each biomass conversion pathway, as input to the LCA. Among the conversion pathways considered, the results of this study essentially confirmed the findings of previous studies highlighting conversion pathways involving electricity and heat provision as environmentally advantageous.

To increase the energetic, technological, economic, and environmental sustainability the sugar beet pulp can be used for the production of electricity in the processes such as landfilling, anaerobic decomposition and as incineration. Production of electricity from bagasse provides better environmental benefits rather than production of electricity from oil and coal. Anaerobic decomposition of sugar beet pulp occurs at faster rate than in the landfill and also gives the best environmental performance than other options. But incineration (sugar beet pulp have the lower heating value of 3.4 MJ·kg⁻¹ on a wet basis [147] of sugar beet pulp for power generation was more favorable environmental process [148].

In the work of Câmara-Salim et al. [147] an environmental assessment of sugar beet pulp and maize stover was performed through life cycle assessment method. In addition, an economic evaluation considering also the costs associated with environmental pollution was conducted. The functional unit was 1 GJ and the impact categories were: climate change, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, and fossil depletion. The economic analysis assessed the internal and external cost indicators. Unfortunately, the results of economic and environmental assessment showed that maize stover has less impact than beet pulp. Maize stover goes through only one agricultural process to be produced, while beet pulp needs an additional pre-processing stage. Moreover, maize stover has a much higher calorific value (16.5 MJ·kg⁻¹ on a wet basis) compared to sugar beet pulp.

To improve the energy recovery and environmental performance without affecting the profitability of the thermochemical and biochemical conversion of sugar beet pulp are conducted advanced scientific studies, taking into account among others novel methods of valorization of sugar beet pulp and novel extraction techniques of pectin. Alexandri et al. [31] and Ioannidou et al. [37] presented a biorefinery concept of restructuring the conventional sugar beet industry into a novel biorefinery. The sugar beet pulp was efficiently fractionated into pectins, phenolic compounds, and a sugar-rich hydrolysate that was subsequently used as fermentation feedstock for succinic acid production—important platform chemical for the development of a sustainable chemical industry, which can be used as precursor for the production of various bulk chemicals, polymers and resins [31]. The components contained in the sugar beet pulp could be effectively converted even to the valuable pharmaceutical intermediates [66]. Simultaneously, the conventional method for pectin extraction (solid–liquid extraction) from sugar beet pulp is a multi-step process (with separation and purification problems) known to be time consuming and expensive. To the increased the technological, economic and environmental efficiency of pectin extraction from sugar beet pulp were applied novel, green extraction techniques. Novel proposals include the eco-friendly extraction of pectins with citric acid as a preliminary step in a simplified biorefinery concept where the pectin-free solid is subsequently subjected to a torrefaction treatment for its upgrading into a commodity solid biofuel [67], subcritical water extraction [149], microwave assisted extraction [102], enzymatic [108,150], and

ultrasound-assisted treatments [150]. These methods offer many advantages [108], such as the reduction of both the extraction time, solvent and reduction of energy consumption, higher extraction rate, and are regarded as environmentally friendly, cost-effective, and possessing great potential for practical applications.

7. Discussion

The need to transition towards implementing the premises of the bioeconomy became a precondition for implementing and executing the principles of the circular economy.

The benefits of such an approach are unquestionable and observable relatively quickly because they refer to extending the product's life cycle and maintaining the high value of materials/feedstock throughout the entire life cycle. One cannot forget about the economic, social, and environmental effects such as: an increase in GDP, an increase in the number of workplaces, reduction in the CO₂ emission, and reducing the rate with which the natural resources are being consumed. In 2019, global sugar beet production was about 278.5 million tonnes [86]. It is estimated that by 2030, annual beet production increases by 8% to 30.8 million tonnes [151]. At the same time, sugar production both from beet and sugarcane is expected to increase by about 16% [151].

The amount of sugar produced affects the production of beet pulp. However, environmental problems caused by sugar production from beet include not only waste production. Other environmental impacts of sugar production are related to herbicide use, lime use, water consumption, energy consumption, and wastewater production [145,152–154]. Energy in the sugar sector is used for crop production in agriculture, transportation of crops, and for beet processing [154].

The sugar industry takes measures to save water, reduce energy consumption and to increase the use of renewable energy [153,154]. There are also studies on LCA applied to sugar production [154] and studies aimed to develop a model to solve problems in production and logistics operations [155].

It means that the significant consequence of closing the loop of the circular economy, especially by means of using, on a larger scale, the renewable biological resources, which are transformed into other added value bio-products, is generating favorable conditions for implementing the premises of the concept of sustainable development. Sustainable development assumes that an important consequence of closing the loops of the circular economy, especially by means of using renewable biological resources generated and converted into other added value bioproducts on a larger scale, is creating favorable conditions to implement the concepts of sustainable development. Sustainable development implies that there is a necessity for interdependence between economic, social, and environmental development.

One cannot ignore the influence of the diverse biological resources (including waste) on the intensification of the development of the bioeconomy. Based on the conducted literature review, it can be said that sugar beet pulp is a valuable and abundant renewable feedstock that has a wide range of actual and potential applications. Attempts are being made to use sugar beet pulp as an important source of pectin. Properties of sugar beet pulp pectin have been determined for example by Peighambardoust et al. [156] and Pacheco et al. [157]. Compared to other commercial pectin sources, pectin from beet pulp have better emulsifying and stabilizer properties [158–160]. Demethylated pectins can be used to the heavy metal ions removal [127]. Dietary fiber sources like pectin may also have therapeutic properties [161,162]. This characteristic allows for the sugar beet pulp to be used as a renewable resource used in the food, cosmetic, and pharmaceutical industries. Research conducted by some of the authors points to interesting applications of the cellulose fibers obtained from the sugar beet pulp.

Optimal use of the pulp is still of scientific, technological, economic, environmental, and cultural significance. It is essential not to waste such a valuable feedstock and to use it fully to manufacture marketable products in economically viable and environmentally friendly ways.

Using sugar beet pulp to produce value-added bioproducts and energy is consistent with principles of sustainability and the circular economy model. The reason is that conversion of beet pulp into marketable products:

- Preserves natural resources and reduces the amount of waste being landfilled by keeping bioresources in the loop [18].
- Exploits various beet components in order to maximize the re-use of the resource and to maximize the added value of secondary products [7,63]. Resulting products and materials have many current and potential applications.
- Reduces GHG and other emissions by producing biogas.

These points took on a special meaning in UE countries, where the amount of sugar produced from sugar beets is especially high. It implies the necessity to use the potential and the possibilities hidden in the appropriate management and utilization of waste in the form of sugar beet pulp. It is worth noting that the vast amounts of sugar produced in Europe and high sugar intake in some of the European countries raise concerns for public health [163]. The reason for concern is that excess sugar intake increases the risk of obesity, dental caries, diabetes, and chronic diseases [164–166]. To reduce sugar consumption, taxes on sugar-sweetened beverages have been introduced in some countries [163]. Since 2021 sugar-sweetened beverages sold in Poland are subject to fee on groceries.

Equally crucial to promoting alternative markets (bioethanol, animal feed, plastics, and chemicals of biological origins) for sugar beets is the stimulation and support of local, regional, and national entities in charge of innovation in the field of byproducts such as sugar beet pulp inter alia by means of funds intended for innovation and low-interest loan programs.

Implementing a circular economy where bioresources and biowaste are converted into valuable products should be perceived as one of the most crucial challenges of the modern world. Economically efficient and environmentally friendly valorization of renewable biological resources can help to mitigate climate change, reduce the world's dependence on non-renewable, fossil resources and support sustainable growth and sustainable society.

Heading towards overcoming the barriers of bioeconomic development it is legitimate to undertake strategic activities, which concentrate on [167]:

- Building a cohesive policy, which takes into account, when constructing the postulates, goals, and instruments within the framework of economic policy and sectoral policies, the premises of the concept of sustainable;
- Material investments, related to infrastructure and non-material investments, which are related to knowledge, qualifications, skills in the area of environmental protection, recycling, sustainable environmental technologies, biotechnology, and bioengineering etc.;
- Implementing the rules of participative management and dialog between the private, public, and non-governmental sector.

The above activities on the operational and tactical level should come down to (more on this subject in lines [44,168]):

- Improving the information flows in the chains and networks of bioeconomy;
- Orienting the educational activity towards sustainable development, bioeconomy, biotechnology, and bioengineering;
- Launching the systems of financial and support and the tools promoting circular economy;
- Implementing the planning, monitoring, and evaluating systems in the chains and networks of bioeconomy;
- Interdisciplinarity of the work conducted in the R&D field;
- Initiating, supporting, and diffusing the research and development work;
- Creating a cooperation network and a network of clusters.

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