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A Short Overview of the Possibilities of Using Waste from the Agri-Food Industry

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ABSTRACT

The agri-food industry is a source of various substrates – plants as well as plant and animal residues or waste, which can be recycled. Determining the yield of agri-food waste processing products that can be obtained from them, as well as estimating the local availability of a given raw material allows for the selection of appropriate substrates that guarantee both their effective production and their continuous supply. The presented article includes a review of scientific reports on the acquisition of bioactive substances, substrates for the production of activated carbon and materials for use in construction from waste from the agri-food industry. Moreover, the article discusses the economic aspects of agri-food waste in terms of bioeconomy.

Keywords: agri-food waste, bioactive materials, activated carbon, construction materials.

INTRODUCTION

Waste means any substance or object that the holder discards or intends or is required to discard [1]. A waste producer is understood as any entity whose activity or existence produces waste (the so-called primary waste producer). In addition, a waste producer is also any entity that carries out pre-treatment, mixing or other operations that change the nature or composition of the waste.

The total amount of waste generated in Poland from 2010 to 2020 is shown in Figure 1 [2]. According to the data of the Central Statistical Office, the production of waste from 2000 to 2013 increased by about 4% and in recent years has remained at the level of ca. 115 million tonnes per year.

Waste management is an important aspect of activities for the protection and shaping of the natural environment. Directives of the European Parliament and the Council of Europe, the so-called framework directives on waste [3] established the hierarchy of waste management, which consists of five main pillars:

a) waste prevention,
b) preparing waste for re-use,
c) recycling,
d) methods of recovery other than recycling, e.g., energy recovery,
e) disposal, including safe storage of waste.

According to the definitions provided by the European Union (EU) on waste, recovery of waste is any process that results in the useful use of waste materials by replacing other resources that would otherwise be used to fulfill a function or an operation whereby the waste is ready to fulfill that function.

Due to the place where the waste is generated, there is a differentiation between municipal and post-production waste. Municipal waste is generated by households and entities dealing with services and small trade. This type of waste is characterized by a large diversity of its composition. Post-production waste is generated in various industries, e.g., in the agri-food industry, healthcare, mining, etc., and is subject to monitoring and supervision. Enterprises producing waste pay fees for their management, from which they must be obligatorily accounted for [4].

Furthermore, agri-food processing is a huge producer of waste as a result of agricultural activities and industrial processing. The waste materials are characterized by certain nutritional, fertilizing, and energetic properties, dependent on the product origin and processing. Therefore, it is crucial to first investigate the waste properties to gain knowledge of its potential. Table 1 presents selected crops produced and the amount generated from them waste annually.

The paper presents the possibilities of reusing agri-food waste most often generated in the Polish production market (Fig. 2). The discussion was divided into four main elements, of which the first chapter discusses the possibilities of recovering bioactive substances from agri-food waste, the second chapter describes the possibilities of using waste for the production of activated carbon, and the third chapter includes considerations on the use of waste substances in the construction sector.

RECOVERY OF BIOACTIVE SUBSTANCES FROM AGRI-FOOD WASTE

Waste from the agri-food industry is a valuable source of bioactive substances, among other compounds from the group of plant antioxidants (e.g., polyphenols, carotenoids). These substances are of great importance in the food industry as natural food additives including antioxidants or compounds with proven health-promoting properties that are ingredients of the so-called functional food. In the pharmaceutical industry, plant antioxidants are ingredients in dietary supplements or active compounds in drugs. Table 2 shows examples of the use of selected wastes from the agri-food industry as a source of bioactive substances of high importance in the food and pharmaceutical industries. Blueberry pomace after processing is an excellent source of anthocyanins – very strong antioxidants and at the same time dyes used in the food industry [14]. In order to isolate them, supercritical fluid extraction (SFE) was used, which

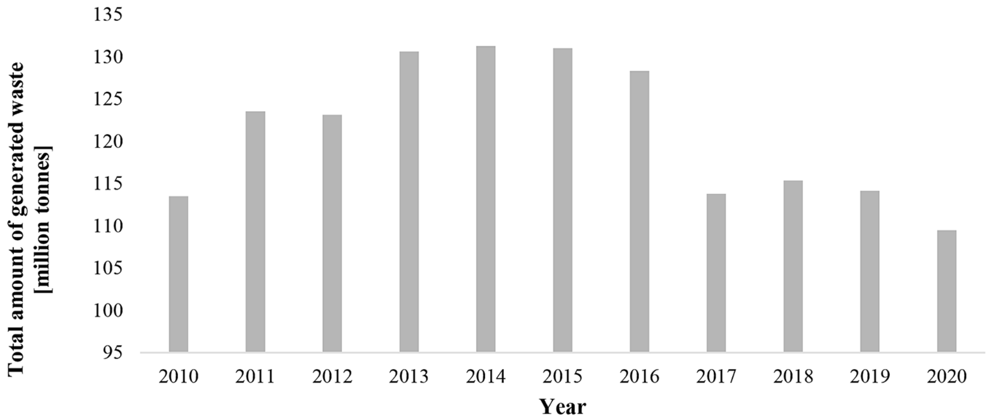

Figure 1. The amount of waste generated in Poland (excluding municipal waste) in the years 2000–2020 according to the Central Statistical Office

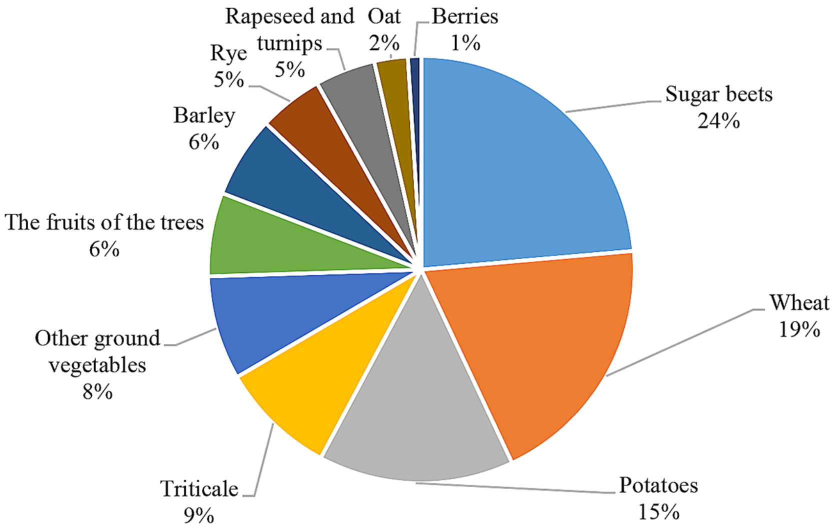

Figure 2. The largest sectors of plant production in Poland in 2010–2020. Own study based on [2]

is an excellent extraction technique that does not require the use of toxic organic solvents and does not generate waste difficult to utilize. For this reason, SFE belongs to the group of techniques consistent with the ideas of green chemistry and sustainable development. SFE was also used to isolate naringenin from grapefruit skins [15], resveratrol from grape pomace [16], polyphenolic compounds from guava seeds [17], pistachio shells [18], green tea leaves [19], beetroot leaves [20], sweet potato biomass [21] or carrot peels [22]. Another extraction technique used in the recovery of bioactive substances from agri-food waste is ultrasound-assisted extraction, which was applied to beet marc [23], potato peel [24], or pistachio shell [18]. Classical simple extraction or Soxhlet extraction (which allows for reduction of the consumption of solvents) are also widely used for the isolation of bioactive biomass components, mainly due to their simplicity and low equipment cost. Waste from the production of tomato juice was extracted in a Soxhlet apparatus in order to isolate lycopene – a dye and a strong antioxidant [25]. The antioxidant fraction from beet leaves was isolated using the same technique [20]. On the other hand, simple extraction (with the use of methanol) of potato peels as well as cauliflower stems and leaves enabled the isolation of a number of compounds from the group of plant polyphenols with strong antioxidant properties (e.g., chlorogenic, coffee, ferulic and sinapic acids, quercetin or kaempferol). The optimization of the extraction process is an important process preceding the actual isolation of bioactive substances from biomass. For this reason, there is a constant search for effective, cheap extraction techniques consistent with the ideas of green chemistry, which will ensure the greatest possible recovery of bioactive substances from plant material, and at the same time will be environmentally friendly.

Table 1. Selected annual crop production in Europe and agri-food waste generation assuming that 100% of the product will be industrially processed

Crop	Waste/by product	Average annually crop production in Europe 2009–2019 [tonnes] [5]	Share of waste in the total crop mass [%]	Waste mass annually [tonnes]
Onion	Onion husks	9567386	37.0 [6]	3 539 932,82
Buckwheat	Buckwheat husks	1270330	30.0 [7]	381 099
Rye	Rye bran	12101793	10.0 [8,9]	1 210 179.3
Plum	Plum stone	2605635	2.8 [10]	72 957.78
Cherry (sour)	Cherry stone	837781	10.0 [11,12]	83 778.1
Potatoes (starch production)	Potato pulp	11555530055 (the share of potatoes processed for starch production is not known)	-	-
		Industrial plant processing potatoes, during the potatoes season uses 150 000 tonnes of potatoes	15.0 [13]	22 500

Table 2. The examples of the use of selected wastes from the agri-food industry as a source of bioactive substances of great importance in the food and pharmaceutical industries

Waste/By-product	Extraction method	Extraction parameters (solvent, temperature, pressure)	Final products	Ref.
Blueberry residues (skin, seeds, pulp)	SFE	CO_2, T=40°C, p=15–25 MPa, t=n.d.	Anthocyanins (178–209 mg/100g of wet mass)	[14]
Grapefruit peel	SFE	CO_2 + ethanol 15%, T=58.6°C, p=95 bar, t=45 min	Naringin (6.8g/100g of dry mass)	[15]
Guava seeds	SFE	CO_2, T=50°C, p=30 MPa, t=n.d.	Total phenolic content (TPC) of the extract 72 mg of gallic acid equivalent (GAE)/100 g of dry mass	[17]
Grape residues (seeds, stems, skin, pomace)	SFE	CO_2, T=35°C, p=400 bar, t=n.d.	Resveratrol (0.4g/100g of dry mass)	[16]
Pistachio hull	SFE	CO_2, T=35°C, p=100 atm, t=15 min	TPC of the extract 6.55 mg of tannic acid equivalent (TAE)/1 g of dry mass	[18]
	UE	Water, t=45 min	TPC of the extract 34.2 mg of TAE/1 g of dry mass	
Green tea leaves	SFE	CO_2, T=60°C, p= 31 MPa t=n.d.	Flavonoids n.d.	[20]
Tomato waste (skins and seeds)	Soxhlet	Acetone:hexane (1:1), t=6h	*Trans*-lycopene(691 μg/g of oil-free dry mass)	[25]
Sweetpotato waste	SFE	CO_2, T=40°C, p=10 MPa, t=2 h	β-carotene (4.73 mg/100 g of dry waste powder), α-tocopherol (0.33 mg/100 g of dry waste powder)	[21]
Potato peels	Simple solvent extraction	Methanol, T≈100°C, t= 0,5- 2h	Quinic acid (0.63–0.71 mg/g of dry mass), chlorogenic acid (1.26–3.87 mg/g of dry mass), caffeic acid (0.72–2.23 mg/g of dry mass)	[24]
Potato peels	UE	80% aqueous methanol solution, T= 30°C, t= 1h	α-chaconine (424–2830 μg/g of dry waste powder), α-solanine (215–750 μg/g of dry waste powder)	[26]
Carrot peels	SFE	CO_2 + ethanol 5–18.4%, T=50–70°C, t= n.d.	Carotenoids (mainly β-carotene (about 60%) and α-carotene (about 30%)) – total carotenoid content recovery 34.9–82.5%	[22]
Discarded carrots	Ultrasound-enzyme assisted extraction	citrate-buffer (pH=5.20), 20 kHz, t=20 min, 5 h of enzymatic treatment, 40°C	α-carotene (52mg/100 g of dry mass), β-carotene (80mg/100g of dry mass), lutein (6.4 mg/100 g of dry mass), α-tocopherol (7.1 mg/100 g of dry mass)	[27]
Beetroot aerial parts	SFE	CO_2 + 7% ethanol, T=40°C, p=250 bar, t= 4h	TPC= 49 mg of GAE/g of extract	[20]
	Soxhlet	Water, T=n.d., t=8h	TPC= 38 mg of GAE/g of extract	
Beetroot pomace	UE	50% aqueous ethanol solution with 0.5% acetic acid, 50/60 Hz, T=22°C, t= 30 min,	Ferulic acid (132.52 mg/100 g of dry mass), catechins (37.96 mg/100 g of dry mass), caffeic acid (7.11 mg/100 g of dry mass), vanillic acid (5.12 mg/100 g of dry mass)	[24]
Cauliflower byproducts (outer leaves)	Simple extraction	80% methanol, T=4°C, t=20 min	Phenolic compounds (ferulic acid, sinapic acid), flavonoids (kaempferol, quercetin)	[28]
Wheat bran	UE	64% aqueous ethanol solution, T=60°C, t=25 min	TPC of the extract 3.1 mg of GAE/g of dry mass	[29]

Note: *SFE – supercritical fluid extraction; UE – ultrasound extraction; n.d. – not defined.

ACTIVATED CARBONS FROM AGRI-FOOD WASTE

The main research paths concerning the management of solid waste from the agri-food industry concerned their use as substrates for direct combustion processes. However, waste biomass is also an excellent carbon source for the production of activated carbons (AC). The advantages of waste include, first of all, low cost, sustainability and ecological suitability. Moreover, activated carbons produced from waste biomass are characterized by high porosity and a large specific surface [30].

There are two main methods of producing activated carbons. Physical activation is a two-stage process, where the first stage is carbonization at 300–900° C in order to obtain a material with a high carbon content [31, 32]. Then, the obtained char is subjected to the action of oxidizing gases (e.g., CO_2, air, steam) at an elevated temperature. During chemical activation, both carbonization and activation processes may occur simultaneously. However, the process is widely performed also in two stages: carbonization or pyrolysis and then activation. During activation, under high temperature conditions, the substrate is exposed to oxidizing agents (most often $ZnCl_2$, KOH, H_3PO_4), which increases the porosity and specific surface of the material [33]. The most important benefits of physical activation are clean, green production with no secondary waste disposal compared to chemical activation [32]. Nevertheless, in the process of chemical activation, the specific surface area of activated carbon and the size of the mesopores obtained are much higher. For example, Nowicki et al. [34] subjected plum kernels to chemical and physical activation, obtaining as a result of the first process over 3.5 times higher specific surface area of AC.

Table 3 presents a summary of process parameters and basic AC properties for selected agri-food waste most commonly found on the Polish market. Among the available literature data, the most common are studies of chemically activated AC and the influence of the activation temperature on the properties of the obtained AC. Mostly, along with the increase in the temperature of the process, the parameters of the AC structure are being improved, however, in the case of materials such as rotten potatoes, potato peelings and plum stones, it should be noted that after reaching a certain temperature optimum, the AC properties deteriorated. Potato peelings, activated with H_3PO_4 at 900° C, showed a specific surface area of only 0.91 m^2g-1, which may indicate the thermal destruction of the AC structure [35].

Activated carbons are an important material used in water and flue gas purification systems due to their large sorption surface and affinity for harmful substances. Their use depends, among others, on pH, operating temperature, metal ion concentrations. AC produced from agri-food waste has been effectively used in water purification systems for heavy metals such as lead, mercury, chromium and cadmium. In addition, their sorption capabilities have been proven in relation to industrially used dyes, such as malachite green, methyl blue, nitrogen dyes (red and yellow), black dyes [55].

In terms of global warming, AC is a material that enables the capture and storage of greenhouse gases such as CO_2, CH_4, H_2 and volatile organic compounds. The sequestration of CO_2 from point emission sources (power plants, waste incineration plants, industrial processes) represents a high AC production potential as a material that can stabilize the amount, and then possibly, reduce the CO_2 content in the atmosphere. According to Abuelnoor et al. [56] CO_2 adsorption by AC is not highly dependent on the activation method used in sorbent production, but rather on the chemical specificity of the AC precursor biomass itself and its ability to form strong covalent bonds or weak Van der Waals bonds with CO_2. For example, AC produced from carrot peelings has favorable sorption properties towards carbon dioxide (chemical activated with KOH) [57].

In addition, AC production from agri-food waste, due to its good conductivity, stability, large and modifiable surface area, has been used in the construction of batteries for portable electric devices and hybrid vehicles, where they are a part of the so-called supercapacitors [58,59].

APPLICATION OF AGRI-FOOD WASTE IN CONSTRUCTIONS

Billions of tonnes of waste are generated every year in Europe alone. The largest part is taken up by construction waste.

Population growth brings with it a greater need for food. Therefore, the agricultural sector increases its efficiency, which results in the generation of a large amount of agri-food waste. The most frequently produced agricultural and food wastes are, apart from hemp, sugar cane leaves and pomace, rice and corn husks, barley husks, egg shells, coconuts, nut shells and wheat straw residues. These wastes can be successfully used in building materials. Natural waste is more and more often used as raw materials to create modern, ecological products, as fillers or substitutes for classic mineral raw materials (e.g. instead of aggregates). This approach is conducive to the reduction of waste produced as a result of the functioning of the economy sectors, but also fits perfectly into the policy of sustainable development and the increase in popularity of the use of alternative, waste materials, while protecting the natural environment [60,61].

Pappu et al. [62] state, for example, that waste from the food industry can be used, among others, in cement and building materials. Up to 20% of production energy can be saved by introducing rice husk or peanut shells in the production of wall boards. Rice and wheat straw and husk,

Table 3. Activated carbons from selected products and agri-food waste present on the Polish market

Precursor	Activation method	Activator	Activation temperature [°C]	S [m^2g^{-1}]	V [cm^3g^{-1}]	Yield [%]	Source
Sugar beets	Chemical	$ZnCl_2$	600	647	0.36	-	[36]
			700	889	0.48	-	
			800	1587	0.91	-	
			900	2281	1.50	-	
Wheat straw	Chemical	$ZnCl_2$	700	907	0.511	37.45	[37]
		KOH	700	552	0.387	26.19	
		H_3PO_4	450	1389	-	31.4	[38]
Rotten potatoes	Chemical	$ZnCl_2$	400	986	0.475	36.3	[39]
			500	1234	0.659	31.7	
			600	1348	0.714	30.2	
			700	1217	0.637	26.3	
			800	1052	0.568	24.5	
		KOH	200	960	-	8.7	[40]
Potato peelings	Chemical	$ZnCl_2$	700	1078	0.47	-	[41]
		H_3PO_4 / KOH	500	833	0.44	-	[42]
		K_2CO_3	700	866	0.4	15	[43]
		H_3PO_4	400	904	0.726	-	[35]
			600	1041	2.96	-	
			800	0,91	0.004	-	
	Physical	CO_2	750	402	0.22	94	[44]
			800	467	0.25	90	
			850	627	0.33	83	
			900	890	0.47	65	
Onion husks	Chemical	K_2CO_3	800	1902	1.28	-	[45]
Cherry stones	Chemical	$ZnCl_2$	500	2043	0.68	39	[46]
			800	1389	0.51	38	
		KOH	700	1324	0.74	46.5	[34]
			500	324	0.13	20	[46]
			800	1406	0.56	12	
			900	1842	0.67	5	
		H_3PO_4	400	1350	0.47	47	[46]
			500	1624	0.55	45	
	Physical	CO_2	800	361	0.21	86.4	[34]
Plum stones	Chemical	KOH	800	2174	1.09	43	[47]
		NaOH	780	1478	0.815	-	[48]
		H_3PO_4	500	829	0.418	-	[49]
			800	329	0.155	-	[50]
	Physical	$H_2O_{(steam)}$	750	354	0.194	-	[51]
		$H_2O_{(steam)}$	900	1162	0.536	-	[52]
Barley straw	Chemical	H_3PO_4	450	1150	-	31.4	[38]
	Physical	$H_2O_{(steam)}$	700	552	0.2576	29.86	[53]
			800	534	0.2994	15.19	
		CO_2	700	211	0.083	23.35	[53]
			800	759	0.3175	9.87	
Rapeseed straw	Chemical	KOH	750	961	-	-	[54]

Note: *S* – total pore area, *V* – total pore volume cotton stalk, Saw mill waste, ground nut shell, banana stalk and jute, sisal and vegetable residues could be recycled and used to produce: particle boards, insulation boards, wall panels, printing paper and corrugating medium, binder, fibrous building panels, acid proof cement, coir fibre, polymer composites, cement board.

Also Kreiker et al. [63] reports that the use of ash from peanut shells up to 15% of the mass of cement improves the compressive strength of composites. Alabadan et al. [64] also investigated the possibility of using groundnut shell fly ash as a partial replacement for Portland cement in concrete. It turned out that the strength of concrete with such fly ash is higher than that of classic concrete and it has been shown that it is possible to replace up to 30% of the cement weight with fly ash. Fly ash from the incineration of agricultural and food waste can also be used in the production of bricks and other building materials. Such solutions reduce production costs, but also improve product properties [46].

Another example of the use of waste is the growing popularity of biochar, produced, for example, from food and wood waste as a so-called green admixture for cement mortars [65]. Gupta S. et al.2018 [65] studied the use of biochar made from mixed food waste, rice waste, and wood waste (mixed wood sawdust) as a carbon sequestering additive in mortars. The carbon content in these chars is 71%, 66%, and 87% by weight, respectively. The results show that the addition of 1–2 wt. Adding biochar to the mortar results in an increase in strength by up to 20% more than for composites without biochar and up to 60% by reducing the degree of water penetration. Studies show that biochar from food waste and mixed wood sawdust can be successfully used as an additive to cement mortar, which is also an excellent example of recycling this waste.

Bricks made with the addition of rice husks during heat treatment become porous due to the burning of organic material. It was observed that the higher the share of rice husks in brick, the more porous the product is, and thus its thermal insulation improves. The usefulness of rice hulls mainly depends on the chemical composition of the ash, especially silica. The properties of rice husk ash have been found to be superior to other additives such as slag, silica fume, and fly ash [66].

The use of hemp fibres for geopolymers

Hemp fibers can also be used for concrete as a substitute for sand in geopolymer composites [67]. Hemp is a fast-growing renewable material. It has been proven that using it as an aggregate substitute causes a decrease in the strength properties of geopolymer mortars. Satisfactory results were achieved by replacing 2.5% (by volume) with hemp instead of standard sand (40 MPa for compressive strength and 6.3 MPa for flexural strength). An increase in the water absorption of the geopolymer composite to 10.2% was also observed due to hemp, which, due to its structure, is characterized by very high water absorption. To prevent this, hemp should be chemically coated/impregnated before use in the composite to prevent moisture absorption [67, 68].

The use of sawdust and reed in cement composites

Economic development, growing awareness of society, and economic reasons force the industry to search for new building materials, preferably from renewable raw materials. It becomes crucial also the use all possible waste materials, supplementing natural resources, which is a pro-ecological part of the sustainable development strategy. Due to the limited resources of rock aggregates, the desire to obtain lighter structures and the need to use the waste from industry, forestry, and agriculture, are aimed at the popularization of the use of waste aggregates from lightweight concrete.

The researchers present [69] the results of tests of selected properties of cement composites with organic fillers in the form of sawdust and reed. The compatibility of both admixtures and the purposefulness of their use were established, thanks to which it is possible to obtain cement composites with good physical and mechanical properties. The fluidizing admixture in combination with the sealing admixture gives the tested composites hydrophobic properties, thanks to which the tested properties were improved compared to composites without additives. Thanks to the addition of a fluidizing admixture in the amount of up to 1% and of the sealing admixture up to 3% in relation to the cement mass, water absorption up to 30%, and compressive strength of approx. 4 MPa were obtained, which increases with increasing admixture content. Cement composites with an organic filler, as highly porous materials, are absorbent materials. The amount of water absorption depends on the internal structure. The biggest porosity of the composite results in higher water absorption, and the lower volumetric weight and compressive strength. Therefore, the tested organic materials requires additional protection against weather conditions, e.g., in the form of external plaster. Cement composites with organic fillers, due to their lower weight than conventional concrete, can be a full-value material for the renovation of old ceilings, the need to relieve structures, and during the superstructure of facilities. Very low apparent density may indicate that cement composites with organic fillers can better protect buildings against heat loss. On the other hand, the acoustic insulation of the tested materials contributes to better sound attenuation compared to standard concrete. The tested cement composites, due to the similar structure and properties to the chipped concrete used in construction, can be used as an insulating, constructional, and sound-absorbing material for acoustic screens. The conducted research confirmed the possibility of using plant waste materials for the production of ecological products.

CONCLUSIONS

Increasing consumption is generating a variety of waste fractions from the agri-food industry, often with economically beneficial properties. Despite the development of recycling technologies, the majority of waste products are still subjected to disposal processes through landfilling, making them a major source of concern in developed societies. Large volumes of waste are making waste management increasingly costly and problematic. In addition, the increase in the production of consumer goods and the increased supply of energy, combined with industrial development and inadequate management methods, are leading to the accumulation of large amounts of waste. Agro-food waste is largely organic waste, which has a noticeably large carbon footprint because it undergoes a rotting process that produces greenhouse gases that affect climate change.

The specific characteristics of agri-food waste mean that its storage is a waste of valuable raw materials with a high potential for utilization. The use of agrifood waste for the extraction of bioactive compounds, the production of activated carbon, or for use in the production of building materials is part of the bioeconomy, which is based on the implementation of the concept of sustainable development. The theory of sustainable development assumes the realization of established economic goals with the least possible use of natural resources and minimization of the negative impact on the economy by means of modern technological solutions. In addition, the use of waste from the agri-food industry ties the bioeconomy to other scientific fields such as biotechnology, medical science, agricultural and food science, environmental science, and economic and social science.

In addition, the reuse of waste from the agro-food industry is part of the concept of a closed-loop economy, which emerged as an alternative to the linear model of raw material use. The essence of a closed-circuit economy is the circular, non-linear flow of resources with the lowest possible use of natural resources and the lowest possible impact on the environment through the use of various technical solutions. How the life cycle of raw materials should proceed is indicated by the 3R principle (reduce, recycle, reuse), which is at the core of the concept of a closed-loop economy. The reduce principle refers to reducing inputs of raw materials while increasing production efficiency. The recycle principle refers to the ability to transform waste in such a way that it can be reused, as reflected in the reuse principle. Reuse captures agri-food waste as an input in co-production processes, assumes resource substitution, and takes into account multi-functional goods.

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