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METHODS FOR THE VALORISATION OF AGRI-FOOD WASTE ACCORDING TO THE CIRCULAR BIOECONOMY CONCEPT

KIERUNKI ZAGOSPODAROWANIA ODPADÓW ROLNO-SPOŻYWCZYCH W BIOGOSPODARCE O OBIEGU ZAMKNIĘTYM

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Abstract: Waste management represents a global and ever-growing issue attracting more attention according to environmental, ethical, social and economic implications. Some of the most significant waste produced globally is generated in the agri-food sector (AFS). AF residues often represent a resource of valuable substances that should be recycled and reused. Making full use of the potential in AF waste (AFW) is in line with the concept of a circular bioeconomy. This approach is consistent with the strategic elements of sustainable development, according to which the economy and society are being reorganised. The full utilisation of secondary raw materials associated with transforming primary waste into raw materials for further production increases income for entrepreneurs and reduces risks to the environment. This paper presents the concepts and legal basis of the closed-loop bioeconomy in the European Union and the metathesis of waste management from the AFS according to this model.

Keywords: circular bioeconomy, sustainble developmeny, agri-food waste, waste management hierarhy, SCP, biodegradable composites.

Streszczenie: Gospodarka odpadami stanowi globalne i stale zyskujące na znaczeniu zagadnienie, które przyciąga coraz większą uwagę ze względu na implikacje środowiskowe, etyczne, społeczne i ekonomiczne. Jedną z największych mas odpadów wytwarzanych na świecie generuje przemysł rolno-spożywczy (PRS). Pozostałości PRS niejednokrotnie stanowią zasoby cennych substancji, które powinny być poddawane recyklingowi i ponownie zagospodarowane. Pełne wykorzystanie potencjału odpadów PRS (OPRS) jest zgodne z koncepcją biogospodarki o obiegu zamkniętym. Podejście to koresponduje ze strategicznymi elementami koncepcji zrównoważonego rozwoju, zgodnie z którymi reorganizowana jest zarówno gospodarka, jak i społeczeństwo. Pełne wykorzystanie surowców wtórnych, związane z przekształcaniem odpadów w surowce do dalszej produkcji, zwiększa dochody przedsiębiorców i zmniejsza zagrożenia dla środowiska. W niniejszym opracowaniu przedstawiono koncepcje i podstawy prawne biogospodarki o obiegu zamkniętym w Unii Europejskiej oraz metatezę gospodarki odpadami funkcjonującej według tego modelu.

Słowa kluczowe: biogospodarka cyrkularna, zrównoważony rozwój, odpady rolno-spożywcze, hierarchia postępowania z odpadami, białko jednokomórkowców, kompozyty biodegradowalne.

1. Introduction

The combination of economic development with environmental protection and social justice following sustainable development goals is a fundamental and overarching objective of the European Union. The pursuit of the continuous improvement of quality of life and well-being of the present and future generations leads to a reflection on the threats posed by the overexploitation of natural resources, irresponsible production and ever-increasing consumption while disregarding the natural environment. The progressive anthropopression of the environment, the associated degradation, and sometimes the annihilation and consequent loss of biodiversity are inevitable if the principles of sustainable development are not implemented effectively, with full awareness and consistency (Zarębska, 2017).

The sustainable development of agriculture and the food industry in the following decades will depend on the application of new concepts and paradigms in manufacturing practice, which can significantly affect the change of existing production systems and the way of thinking and functioning of societies. Essential and widely discussed concepts that are also essential tools for achieving sustainable development goals are the Circular Economy (CE), Bioeconomy and the synergy of both, the Circular Bioeconomy (CBE). These concepts have many correlating standards and postulates, such as increasing the use of renewable biological resources and the efficient management of natural resources and energy to ensure the sustainable development of economies and businesses. The basic premise of these concepts is the need to transform the economy based on the under-utilisation of processed raw materials and conventional energy sources into a knowledge-based economy, prioritising sustainable production and renewable energy sources through biotechnology and innovation.

Implementing the CE and CBE concepts can be an effective remedy to the constantly growing amount of waste and pollution in Europe, which is increasingly threatening its inhabitants' economic and social well-being. Implementing CBE methods will make it possible to increase the competitiveness of European companies, whose main waste masses, suitable for further use or effective recovery, are produced in the agri-food sector (Gralak, 2021).

From the point of view of further use as potential feedstock, agri-food waste (AFW) represents a valuable resource of materials with high energy and nutritional potential associated with a high content of carbohydrates, vitamins, fibres, valuable fats, proteins, pectin and other mineral compounds, which predisposes them to secondary use to the greatest possible extent (Gebremikael et al., 2020).

This article aimed to introduce the concepts of CBE and present a review of AFW waste management methods, following the presented metathesis, to obtain value-added products.

2. Circular economy, bioeconomy and waste in European Union legislation

Implementation of sustainable development goals in Europe is supported by the formalisation of the provisions and recommendations included in various documents, such as conventions, treaties, directives, laws, strategies, plans, communications and environmental management tools as well as environmental protection programmes. A crucial document within the Decision of the European Parliament and of the Council of 22 July 2002 laying down the Sixth Community Environment Action Programme in Communication from the Commission to the European Parliament, the Council, the European Economic And Social Committee, and the Committee of the Regions dated 2 July 2014, COM/2014/0398 final: *Towards a circular economy: A zero waste programme for Europe*, supplemented in 2015 COM/2015/0614 final: *Closing the loop – an EU action plan for the circular economy*. According to the Communication, a "closed-loop economy" means eliminating the concept of "waste" and assuming that all created and recycled matter has value (Internet 1). The proposed transformation implies a change from a productivity-driven mindset in manufacturing technology to an approach focused on product usability, regardless of the "life cycle". This approach necessitates a change in the way we both design and think about products, taking into account the entire product life cycle, while at the same time creating a deeper relationship with consumers that goes beyond the moment of sale and develops in the after-sales period (Lacy and Rutqvist, 2015). In addition, the CBE concept eliminates the concept of "end-of-life products", replacing it with "reuse", recycling and recovery of materials (Kirchherr et al., 2017) through appropriate product design (i.e. eco-design) (Schultze, 2016).

The bioeconomy is a widely discussed policy issue in recent years and a strategic implementation tool used in economic practice, it is also a key approach to solve growing socio-economic problems in Europe. With its development, it is possible to achieve sustainable development goals such as ensuring food security, increasing the use of renewable resources while reducing dependence on non-renewable resources, mitigating climate change, and thus ensuring sustainable economic growth (Gralak, 2021).

According to the definition developed by the OECD, the bioeconomy is: "the activity of applying biotechnology, bioprocesses and bioproducts to create sustainable, environmentally sound and competitive products and services" combining elements such as biotechnological knowledge, the use of renewable biomass and the application of the aforementioned in various productive activities (OECD, 2009).

The definition of the bioeconomy proposed in the Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, “A sustainable bioeconomy for Europe: strengthening the links between the economy, society and the environment”, 11 November 2018, COM/2018/0673 final, states that: “the bioeconomy encompasses all sectors and systems that operate on the basis of biological resources (animals, plants, micro-organisms and their derived biomass, including organic waste), their functions and principles” (Internet 1).

The German Bioeconomy Council defines the bioeconomy as “the production, use, and conservation of biological resources, including related knowledge, science, technology, and innovation, to provide sustainable product and process solutions in all sectors of the economy and to enable the transformation towards a sustainable economy” (German Bioeconomy Council, 2018).

The bioeconomy and the CE are among the most important tools for implementing the principles of sustainable development, enabling the reduction of the effects of over-exploitation of natural resources, while at the same time providing an opportunity to reduce waste, pollution and greenhouse gas emissions (Pink and Wojnarowska, 2020).

The transformation of the current economy to a CBE, in which the value of resources, materials and products is maintained for as long as possible, relies strictly on reducing waste generation to a minimum. Waste management plays a fundamental role in determining the effectiveness of the application in the practice of the waste hierarchy, presented in Figure 1, according to Article 17 of the Waste Act of 14 December

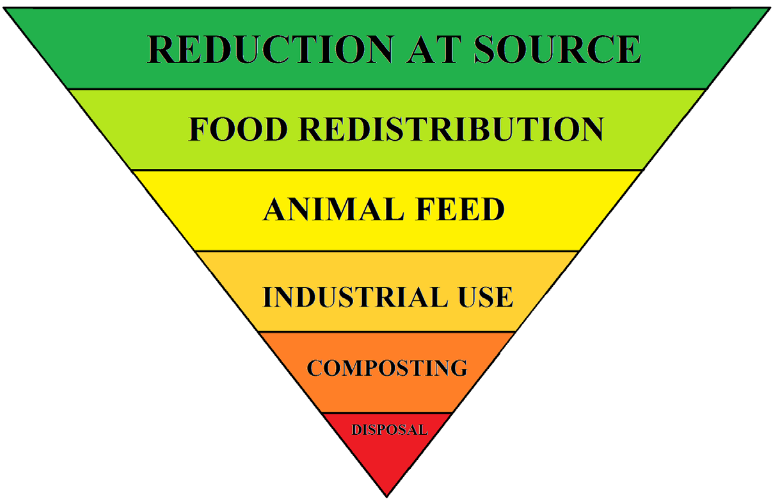

Fig. 1. Waste management hierarchy

Source: own elaboration.

2012 (see Journal of Laws 2019.0.701 and COM/2015/0595 final – 2015/0275 (COD): Directive of the European Parliament and the Council amending Directive 2008/98/EC on waste; starting from prevention of waste generation, preparation for reuse, recycling by recovery processes up to disposal (Internet 1; Rataj, 2019)).

The definition of waste in the EU is set out in current legislation but is still being debated. According to Article 3(1) of Directive 2008/98/EC, "waste is any substance or object the holder discards or intends or is required to discard". This definition covers all objects, solids, and liquids resulting from industrial, economic or human activities, which are useless in the place and time generated (Gharfalkar, Court, Campbell, Ali, and Hillier, 2015).

However, as a closed system in the ecosystem, it is impossible to talk about waste as unusable substances in general, at most as temporarily unusable substances. The statement, which complements the definition of waste, namely that "waste is a raw material, but not in the right place at the right time", is accurate (Chmiel, 1999). This notion is in line with the implementation concepts for the CBE, according to which circulating elements in the economy should be considered as potential resources until determined otherwise (Park and Chertow, 2014; Rataj, 2019).

2.1. Waste and by-products of the agri-food sector

Agro-industrial waste are materials obtained from various processes realised in agricultural and agriculture-related industries related to the production of outcomes such as fruits, vegetables, meat, dairy products, etc. (Cusenza et al., 2021). Agri-food waste (AFW) and by-products are potentially edible materials for humans that are discarded, lost or degraded instead used in human food production (Parfitt, Barthel, and Macnaughton, 2010). The AFS produces huge amounts of residual materials and substances, treated in different ways depending on technological, economic, political and geographical circumstances (Schmidt et al., 2021).

According to COM/2015/0595 final – 2015/0275 (COD), to clarify the definition of waste generated in the CE, a clear distinction should be made between by-products and waste. The decision that a substance is not a waste but a by-product thus allowing its further use following all product characteristics, should be consistent with the objectives of protecting the environment and human health (Internet 1).

However, these criteria are ambiguous and problematic because the same type of residue may be considered waste or a by-product depending on the social, economic and legal conditions. Examples of such by-products are molasses or pulp produced in sugar factories, which, despite potential use for feed purposes or the production of nanocellulose, have not been in demand recently and therefore have to be classified as waste (Olędzki and Walaszczyk, 2020; Sumińska and Sierakowska, 2019). Ultimately, any unused and undefined product acquires waste characteristics but becomes a raw material when managed (Kowalczyk, 2021).

The total amounts of food waste in the EU are around 700 million tons annually (Gebremikael et al., 2020). However, it is not possible to determine the exact amount of waste arising from the AFS in Europe due to, among others, the large variety of production companies, their dispersion, different production scales and incorrect classification. For these reasons, identifying both the problems and needs related to the management of waste from AFS is problematic due to the misclassification of bio-waste, and is often diverted into the municipal waste stream, which theoretically exempts agri-farm owners from the need to keep records of waste. This situation directly contributes to the generation of a significant amount of pollution in the environment and to a kind of waste resulting from the failure to use the physical and chemical potential of AFW. Moreover, each tonne of AFS waste produced in the fruit and vegetable industry, distilleries, breweries and milk processing plants, generates 4.5 tonnes of carbon dioxide emissions annually (Kopik, 2019), which does not correspond to the current assumptions and goals of the concept of sustainable development and sustainable production concerning reducing greenhouse gas emissions by 2030 (Internet 2).

AFW is characterised by properties used in agriculture, feed and energy industries. It has specific nutritional properties and is biodegradable, making it good material for research involving microorganisms in a CBE (Gebremikael et al., 2020). Due to its properties, such as biodegradability and ease of re-circulation, in most cases AFS residues, including biomass, are highly desirable feedstock in a CBE.

3. Agri-food waste management in a circular bioeconomy

The proper utilisation of AFW should be cascaded (Olsson et al., 2018), i.e. according to the order of priority, enabling the highest value-added from it. The cascading steps enable the preservation of the quality of the resources contained in AFW by following the bioproduct value pyramid and the waste hierarchy. According to the hierarchy, as for an example with biomass, it should be used first for food production, then as a raw material for the chemical, pharmaceutical, paper and building materials industries, and the production of organic fertilisers (Olsztyńska, 2018).

In a CBE, biomass, or other residues from the AFS, used for energy purposes, can only occur when other management options have been exhausted, which makes it impossible to maintain its value through reuse or recycling. In addition, only biomass waste and waste from the final recycling stages should be used for energy production, in addition to energy crops (Carus and Dammer, 2018). Applying the correct hierarchy by cascading the residues from the AFS by reusing them in several cycles, or recycling them, will allow for an extended period of maintaining their added value in a CBE.

Table 1 (Appendix) presents the waste and production residues generated in the leading agri-food industries in Europe, together with an assessment of the potential for use for food, feed, agricultural and energy purposes, according to the CBE waste hierarchy.

One of the options to recycle AFW is to apply it directly or as after-treatment processes to agricultural land. Due to the possible content of heavy metals, toxic organic compounds and the presence of pathogenic microorganisms, certain methods are used to effectively improve their sanitary status, such as composting, fermentation, electrodialysis, oxidation, pyrolysis, incineration (Daniel et al., 2012).

The most common treatment methods include composting, anaerobic digestion, and incineration (Frączek, Hebda, and Łapczyńska-Kordon, 2012). AFW is primarily biodegradable, i.e. the so-called bio-waste, providing material for biological waste treatment, which includes composting and anaerobic digestion using the natural metabolic processes of microorganisms to achieve decomposition, or the transformation of the organic matter contained in it into products that can be returned to the natural cycle of matter (Jędrczak, 2008). Composting is the process by which organic waste is decomposed into what is called compost, which is a unique organic fertiliser. The decomposition of organic components occurs with the participation of microorganisms – bacteria, fungi and radicles. All biodegradable waste from both human and industrial activities is suitable for compost production. Successful composting methods require the use of proper techniques such as mechanical treatment, sorting, shredding, and selecting appropriate bioreactors (Cerda et al., 2018).

Fermentation is the process commonly used to treat concentrated wastewater and treatment waste from the paper and AF industries. Anaerobic digestion is the biological decomposition of bio-waste by microorganisms under controlled conditions. It produces biogas (a mixture of carbon dioxide, methane and traces of other gases) or bioethanol (biodiesel) and fermented material. Their use, especially for the production of biodiesel, eliminates the problem of the need to use valuable crops, which, used for this purpose, affect the increase in food prices (Gong et al., 2021; Hafid, Omar, Abdul Rahman, and Wakisaka, 2021).

The combustion of biomass, all kinds of organic substances of plant or animal origin, is used in the energy industry. This method is the most radical among the above mentioned. To a large extent, it allows eliminating waste with the simultaneous generation of energy and heat. The residues after incineration, such as ashes, find their further use, e.g. in construction. This method also makes it possible to generate heat and energy, which can be used in the facility where they are produced, while it contributes to an increase in greenhouse gas emissions to the atmosphere (Demirbas, 2004; Palanivelu, Ramachandran, and Raghavan, 2021). The application of the processes mentioned above makes it possible to utilise further the residues generated in several branches of the AF industry.

Apart from traditional techniques using microbial action to produce biogas or bioethanol, other methods of processing AFW using biotechnological techniques are also implemented, mainly for production of microbial biomass, metabolites and substrate utilisation (Pandey, Soccol, Nigam, and Soccol, 2000).

Depending on the applied technologies, different microorganisms are employed and, consequently, also different technological requirements (Kot et al., 2020). The processes conditioned by the activity of microorganisms or enzymes of their origin require knowledge of the physiology and biochemistry of industrial microorganisms.

This group includes many species of bacteria, fungi, actinomycetes and viruses; due to their unique properties, such as the rate of metabolism, the variety of chemical reactions carried out, the ease of controlling both physiological processes and making genetic changes, microorganisms are widely used for the manufacture of various products and the inactivation and disposal of wastewater and waste (Chmiel, 1994).

Moreover, AFW is considered to be a conventional substrate for the biotechnological production of biomass, protein concentrate, amino acids and Single Cell Protein (SCP). Microorganisms such as bacteria, yeast, fungi, and algae, utilise expensive feedstock such as starch, molasses, fruit and vegetable wastes, and unconventional ones, e.g. petroleum by-products, natural gas, ethanol, methanol lignocellulosic biomass. SCP is the protein obtained from microbial sources with high protein content. Moreover, it contains fats, carbohydrates, nucleic acids, vitamins and minerals and is rich in certain essential amino acids such as lysine and methionine, limited in most plant and animal foods. The use of SCP in food production may lead to a decline in protein deficiency in the world's population (Suman, Nupur, Anuradha, and Pradeep, 2015).

Lignocellulosic waste is generated in many AFS branches, however, due to the structural characteristics of the lignocellulosic complex, it must be pre-treated before use, allowing microbes access to the simple sugars they then utilise (Schacht, Zetzl, and Brunner, 2008). Pre-treatment is crucial for the release efficiency of the polysaccharides contained in plant biomass. Biological, chemical, physical and physicochemical methods are used resulting in increased cellulose availability to hydrolytic enzymes (Alvira, Tomás-Pejó, Ballesteros, and Negro, 2010). After treatment, this waste can be employed as a carbon and energy source in biotechnological processes, such as in the production of SCP-rich foods and feeds. Lignocellulosic waste is used, among others, as substrate for the cultivation of edible fungi or in obtaining bacterial biomass and yeast. However, biomass production from these raw materials is not economically viable. In most of the technologies developed so far, concerning both deep and surface cultures, materials such as cereal, rice and rapeseed straws, cereal husks, corn stover, sunflower seeds and waste from the fruit and vegetable industry were used. However, the price of the produced products is many times higher than the price of soy protein (Hussain, Sajjad, Khan, and Wahid, 2019). Yet, it can be assumed that different feedstocks' lignocellulosic hydrolysates can be applied as substrate for industrial fermentation, and thus upgrade the value of these feedstock waste (Rumbold et al., 2009).

The proper strategy for the valorisation of lignocellulosic agri-residue related with a CBE is its bioconversion to second-generation biofuels, or briquetting and biogas production (Awasthi et al., 2019; Xiao et al., 2017).

The bioconversion of crop waste occurs during the oleaginous process, acidogenesis, photosynthesis, fermentation, methanogenesis, solventogenesis, etc. (Qin et al., 2021). According to a CBE, this waste should be exploited in the biorefinery or in bio-based materials production (Phairuang et al., 2019).

3.1. Sugar industry waste

The organic waste is generated in the sugar industry, processing sugar beet, beet pulp, molasses and waste vegetable matter. Waste vegetable matter and beet pulp find their way into fertiliser production after treatment, but are more suitable for animal feed, biogas, food pectin, pectin glue, dietary fibre or lactic acid or sugar recovery (Bednarski, Adamczak, and Krzemieniowski, 2003).

From the perspective of producing valuable substances from beet pulp, pomace can extract and produce many valuable chemical compounds such as D-galacturonic acid, L-arabinose, D-glucose, D-galactose, L-rhamnose, and D-xylose used in food, pharmaceutical, and cosmetic industries. Moreover, beet pulp can produce furfural, ferulic acid, succinic acid, used as fuels, plastics, solvents, or bio-renewable copolymers and chemicals (Ptak, Skowrońska, Pińkowska, and Krzywonos, 2022).

Furthermore, cellulose in beet pulp can be converted into carboxymethyl cellulose, and is used in the food, cosmetic, and pharmaceutical industries and in drilling mud and detergents. Sugar beet pulp has also served to obtain biodegradable composites (thermoplastics), biocompatible material at high-temperature applications, and can be used as a partial substitute for wood fibres in paper production, e.g. for printing and photocopying (Ptak et al., 2022).

For decades, beet molasses has been utilised as a feedstock or low-cost nutrient for bacterial growth and biobased products. For further promotion of the utilisation of molasses in a CBE, most studies focused on producing green products (H2, P3HB and/or biodiesel) culturing purple bacteria on different effluents and strategies as single (or two-stage, e.g. dark-fermentation followed by photo-fermentation (Gojgic-Cvijovic et al., 2019). With the use of molasses, clean energy (H2) and bioplastics can be obtained which may contribute to cutting the cost of biobased products (Carlozzi et al., 2019).

The biotechnological use of molasses includes biomass production and metabolites, directly related to its utilisation. Microbes that use sucrose as a carbon source are multiplied in the molasses medium (Baumann and Westermann, 2016), including baker's yeast and feed yeast (Bednarski et al., 2003). In addition, cane or beet molasses is used for the biosynthesis of citric acid, both by the deep method as well as the surface method (Leśniak, Pietkiewicz, and Podgórski, 2002).

Moreover, molasses can be used in SCP production, and this depends on the price, availability, and composition of molasses (Spalvins, Ivanów, and Blumberg, 2018). Cultivating yeasts such as *Candida tropicalis*, *Kluyveromyces marxianus*, and *Saccharomyces cerevisiae* enables the production of high-quality protein ranging from 24%-54% of the protein in dry weight (Aggelopoulos et al., 2014; Gao, Ki, and Liu, 2012).

3.2. Dairy industry waste

The dairy industry has a well-developed hierarchy chain in a CBE for bio-residuals, with various products from whey being shaped by market demand. The production of every kg of cheese requires 10 kg of milk resulting in 9 kg of whey production (Prazeres, Carvalho, and Rivas, 2012). Historically, whey was a waste, the contaminated effluent contains proteins, salts, fatty substances, lactose, and various cleaning chemicals, which without expensive sewage treatments constitutes a significant source of environmental pollution.

Whey is an AFW with high organic content and nutritional value, from which one can extracted compounds such as lactic acid, peptides, proteins, substrates, lactulose, etc. The high content of lactose and other nutrients essential for microbial growth predestine whey to a potential raw material for the production of various bio-products through biotechnological processes. Whey components can be reformulated in the production of alcoholic beverages, processed food and flavourings in dairy products or sweet syrup for use in other products and health and functional foods by applying lactose and a complex of minerals to dietetic foodstuff (Gregg et al., 2020). Some of the effects of whey protein include activating natural killer cells and neutrophils, inducing colony-stimulating factor activity, and enhancing macrophage cytotoxicity (Marshall, 2004). Due to its anti-inflammatory properties, whey is used as an exercise treatment, a protein supplement, and can also be used in pharmaceutical and cosmetic products (Mollea, Marmo, and Bosco, 2013).

In accordance with CBE strategies, some countries are currently producing ethanol from whey, which can also be a raw material for the pharmaceutical and paper industry (Gregg et al., 2020).

Whey is widely used in biotechnological processes. Its utilisation in bioprocesses allows to obtain lactic acid (Carlozzi et al., 2019), propionic and citric acid together with salts, butanol, polysaccharides, ribonucleotides, oligopeptides and SCP (Abbas, 2006). Moreover, it is used to produce other organic acids and vitamin B_2 and B_{12}, plant hormones and carotenes (George, Vincent, and Mackey, 2020).

3.3. Fruits and vegetable industry waste

The processing of fruits, vegetables and crops generate approximately 40%-50% of the total waste produced in the AFS (Sirohi, Gaur, Pandey, Sim, and Kumar, 2021), such as peel, core, stem and crown. It is recommended to use fruit processing waste as livestock feed, or transformed it into bio-fertilizers by composting, as well as a potential source of biomass in the production of biofuels (Banerjee et al., 2017). Such waste is rich in fermentable sugars, and in accordance with a CBE, it can be exploited to produce valuable products, including food, biofuels, bioenergy, and biopolymers (Sirohi et al., 2021).

This waste mass contains valuable bioactive compounds such as phytochemicals (carotenoids, flavonoids, polyphenols, tannins, lignin, etc.), vitamins, enzymes, dietary fibres and oils, which should be reutilised in line with a CBE. This waste is valorised by food, nutraceuticals, pharmaceuticals, cosmetics and the textile sector to produce value-added products for increased revenue generation (Sagar, Pareek, Sharma, Yahia, and Lobo, 2018).

However, food manufacturers do not exploit the full potential of fruit and vegetables raw materials, especially their by-products. A popular method of the re-usage of fruit and vegetable pomace is in producing juices, purees and concentrates fortified with vitamins and bioactive compounds (Łaba, 2012; Żary-Sikorska, Wichrowska, Gozdecka, and Gęsiński, 2015). Fruit pomace can also be added to herbal and fruit teas (Łaba, 2012). Pomace from fruits, such as Aronia (chokeberry), can be successfully used for the production of natural food colourants, which can contribute to the maximum use of fruit raw materials (including waste after production) (Wu, Gu, Prior, and McKay, 2004), in accordance with the CBE concept.

Moreover, waste from fruits and vegetable processing can also be used to produce biodegradable plastics known as Polyhydroxyalkanoates (PHAs) – biologically produced polymers similar to synthetic polymers. Biopolymers can be produced microbially, and its production in 2019 reached \$57 million with a compound annual growth rate (CAGR) of 11.2%, and by 2024 the market size of PHAs is projected to total \$98 million (Sirohi et al., 2021).

The microbial processing of fruit and vegetable waste is widely used to produce vital enzymes and organic acids (Panda, Mishra, and Kayitesi, 2016). Other directions of their use through microbial processing are related to the production of fermented beverages, SCP, single-cell oils, colours, flavours, fragrances, polysaccharides, biopesticides, plant growth regulators, and biohydrogen (Panda et al., 2018).

3.4. Cereal industry waste

Conventionally, organic pollutants such as husks produced by the cereal industry are sent for composting with other organic waste, or to on-site boiler plants for fuel. However, the current managing practices that discharge cereal processing by-products to the environment are not sustainable. It is estimated that 12.9% of all food waste is produced during cereals processing and manufacturing, with an annual amount of waste at around 40,000/45,000 tons/year in Europe (Belc et al., 2019).

Wheat is traditionally considered the most popular cereal for human consumption. Its manufacturing path to produce wheat bran as the main by-product obtained from milling and flour production (Viuda-Martos, Fernández-López, and Pérez-Álvarez, 2019). It is well-known that wheat bran can provide gastrointestinal benefits, reduce the risk of metabolic disorders, cardiovascular diseases, and provide anticancer effects (Deroover et al., 2019). It is possible to isolate from wheat bran soluble and insoluble dietary fibres, including arabinoxylan and glucans, sugars and their derivatives, starch, succinic acid and secondary plant metabolites, including phenolic acids and proteins (Apprich et al., 2014). Thus, it can be used to fortify food product lacing of such components, especially pasta and bread (Alzuwaid, Pleming, Fellows, and Sissons, 2021).

Another highly valuable source of bioactive compounds of cereal by-products is wheat germ, which accounts for approximately 2% of weight after wheat grain milling. Due to its high content of beneficial molecules such as dietary fibres, amino acids, tocopherols, unsaturated fatty acids, essential fatty acids (linolenic acid) and polyphenolic compounds, it attracted scientific attention (Viuda--Martos et al., 2019). Several studies have demonstrated that the use of wheat germ in food products, especially in bread, is beneficial and confers a high degree of the added value of functional and nutritional properties (Rizzello, Cassone, Coda, and Gobbetti, 2011).

In addition, waste materials such as grain hulls can be used to produce biocomposites. Microfibers from grain hulls, after enzymatic modification of their surface, can be an effective reinforcement for biocomposites based on resin biocomposites with properties not worse than classical epoxy composites containing wood fibres, or even higher in the case of fracture resistance, which – in a situation of constantly increasing prices and and scarcity of wood around the world – may be its alternative (Urbaniak and Błędzki, 2013).

An effective way to valorise waste from cereal processing is to produce different bacteria and yeast. It was estimated that powdered wheat bran, as an alternative cultivar medium for Bacillus thuringiensis, is fifty times less expensive than the conventional medium (Bti, 2011).

Wheat bran can also be used to produce SCP from Candida utilis and Rhizopus oligosporus (Yunus, Nadeem, and Rashid, 2015).

3.5. Brewing industry waste

The brewing industry produces mineral contaminants suitable for pit filling and organic contaminants directed for composting with other organic material, or burned with fuel. Sludge, grains, floats and sprouts are directed to poultry feed. Malt sprouts are also used in the pharmaceutical industry and find their application in enzyme and amino-acid preparations. Malt dust is suitable for direct field application and is also used for composting. Pulp is used to make silage, or it can be dried and used as an ingredient in feed, just as wort sludge and yeast slurry (Bednarski et al., 2003).

Breweries mostly waste brewer's spent grain (BSG), which is mainly lignocellulosic material (cellulose, lignin, and hemicellulose) composed of fibres, proteins, lipids, ashes, and others (Panjičko, Zupančič, and Zelić, 2015). It is proposed to extract bioactive phenolic compounds from it and to incorporate them into human food in line with the CBE model (Meneses, Martins, Teixeira, and Mussatto, 2013).

Currently, the most popular usage of BSG is for animal feed, especially for cattle (Ferraz et al., 2013). Brewing waste can also be used as a feedstock for biogas (biomethane) and biofertiliser production (Martin and Parsapour, 2012; Panjičko et al., 2015). Moreover, BSG can be treated as an inexpensive biosorbent used to remove industrial dyes' metal contaminants from aqueous solutions, or even from natural water bodies (Contreras, Sepúlveda, and Palma, 2012; Liguori et al., 2012).

BSG can also be used as lignocellulosic carrier for yeast in continuous beer fermentation (Pires, Ruiz, Teixeira, and Vicente, 2012) or as low-cost substrate for lactic acid production for chemical and pharmaceutical applications (Djukić--Vuković et al., 2016).

Furthermore, after biochemical processes decreasing the thermal conductivity of BSG, they can be used for brick production with the advantage over standard bricks of enhancing the open porosity in the brick material with a biodegradable alternative for synthetic pore-forming material (Ferraz et al., 2012).

As being high in carbohydrates, BSG can be employed as an energy source for biogas production, as an alternative to conventional materials whose price is related to fertilisers affecting the price of biogas and the costs of feedstock (Martin and Parsapour, 2012).

BSG can also be applied as a substrate in the cultivation of *Kluyveromyces marxianus* to produce SCP with a 59% of protein content in dry mass (Aggelopoulos et al., 2014).

3.6. Slaughterhouse waste

The meat industry is a high waste generating industry. Residuals and by-products from meat manufacturing and processing include organs, blood and plasma, hides and skins, meat trimmings, bones, horns, tallow, lard and other fatty tissues and slaughterhouse wastewater (Okoro, Sun, and Birch, 2017; Toldrá, Mora, and Reig, 2016). Some of them can be recovered, and used further as biomolecules (Baiano, 2014).

Animal by-products consist of valuable ingredients such as amino acids, minerals and vitamins (Toldrá et al., 2016), and can be directly used for human and animal food production and as flavour enhancers (Mirabella, Castellani, and Sala, 2014). Such products are created from residuals that are fresh, frozen, refrigerated, pickled or smoked (sausages from organ meat, cooking fat livestock feed and pet food) (Jayathilakan, Sultana, Radhakrishna, and Bawa, 2012; Salminen and Rintala, 2002; Toldrá et al., 2016). The use in food and feed preparation is regulated by European legislation and policy, including Regulation (EC) 1069/2009 on health rules and the regulation implementing regulations (EC) 142/2011 (Toldrá et al., 2016).

For non-food, non-feed applications, slaughter waste can be used for a range of other products such as gelatin, protein, collagen, enzymes, phosphates and other ingredients processed in the chemical and pharmaceutical industry (Mirabella et al., 2014).

Non-edible products are used as leather, biodegradable packaging or edible meat product casings (Jayathilakan et al., 2012; Toldrá et al., 2016) They can be also be utilised as fertiliser, eco-phosphate from ashes, soil additive, compost, and treated as digestate (Bujak, 2015; Mirabella et al., 2014; Okoro et al., 2017).

Finally, they can be managed in energy production through incineration or fermentation into biogas and the production of biofuels (Bujak, 2015).

Animal fat residues can undergo hydrolysis or hydro-oxy generation and hydroisomerization for the creation of enzymes or for energy production (Mora, Toldrá-Reig, Reig, and Toldrá, 2015, Toldrá et al., 2016). It is estimated that the efficient and sustainable use of slaughterhouse by-products can bring the increase the income from beef and pork by 11.4% and 7.5%, respectively (Toldrá et al., 2016).

The directions of the practical application of waste animal fats and oil sludges are connected with SCP production, citric fermentation and obtaining microbiological lipolytic preparations (Singh, Kuila, Adak, Bishai, and Banerjee, 2011).

4. Conclusions

Applying CBE strategies to the AF industry may lead to achieving sustainable development goals related to diminishing the impact of waste on the natural environment, and providing nutritional and energetic safety for a growing world population.

The value of reutilised residues from AFS chains is influenced by the residuals' materiality, their prospective usage in food production, chemical, pharmaceutical and other industries, and legislation regulation (particularly for disposal). Moreover, the efficiency of a CBE in the AFS is dependent on the technology involved in the transformation and the companies' capabilities to implement sustainable production models that enable the use of low-waste technologies.

Applying the cascade and hierarchy approach in the AFS waste management can contribute to the business objectives of increasing revenues and reducing GHG emissions. It can be said that the implementation of CBE models provides a basis for the proper functioning of an economy based on the sustainable use of natural resources and the valuable by-products contained in bio-waste.

The CBE approach allows producers to add value from the waste generated and produce new products that will return to both the manufacturing and processing markets.

The use of biotechnology in the valorisation processes of AFW makes it possible to produce a range of value-added products, including SCP, the use of which in food technology and animal nutrition may provide an answer to the growing protein deficit. Its inclusion in food can help meet sustainable development goals, including eliminating world hunger.

Research and innovation related to transformation, processing, and valorising bio-residuals are critical components to a CBE.

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Appendix

Table 1. Assessment of the possibility of managing agricultural waste according to the waste hierarchy

Industry	Waste/residues	Food production	Chemical components	Feed	Direct fertilization	Fertilizer	Bio-gas	Bio-Ethanol	Biodegradable composites	Combustion
Sugar	Mud floats				+					
	Beet pulp		+	+		+	+	+	+	+
	Defecation sludge			+	+	+				
	Molasses		+				+	+		+
	Waste crop mass		+	+		+	+	+		
Dairy	Whey	+	+				+	+		
Fruit, wegetable	Pulp	+	+	+		+	+	+	+	
	Waste crop mass		+			+	+	+	+	
Cereal	Bran	+	+	+		+		+		
	Germ	+	+	+		+				
	Husk			+		+			+	+
Brewing	Brewer’s spent grain	+		+		+	+	+	+	
Meet	Organic wastes	+	+	+ –		+	+	+	+	

* + – the possibility of using the element in a selected method.

Source: own study based on a literature review.