SUSTAINABLE VALORIZATION OF AGRI-FOOD WASTE AS A SOURCE OF BIOACTIVE COMPOUNDS FOR OBTAINING FUNCTIONAL FOODS IN THE CONTEXT OF THE CIRCULAR ECONOMY

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REVIEW

Abstract

Agro-food waste is an important source of bioactive compounds for both human and animal health. Therefore, transforming these wastes into high value products could be an optimal solution for reducing the burden of waste management, decreasing resource and energy consumption, and protecting the environment. For the sustainable valorization of agro-food waste, new and innovative technologies have been developed for the extraction of bioactive compounds to enhance industrially processed foods or to improve the quality of animal-based foods (milk, meat, eggs) by incorporating these wastes into animal diets. The use of these sustainable technologies offers various advantages, including waste reduction, establishing new economic perspectives, promoting a circular economy, and the development of functional foods and nutritional supplements. One of the main challenges for the future will be improving the efficiency of extraction processes and developing new methods that are more efficient and environmentally friendly. Additionally, it is necessary to establish the bioavailability and safety of the extracted compounds, considering that agro-food waste from which they are extracted deteriorates rapidly and may contain a series of mycotoxins and toxic chemicals from agricultural production. Furthermore, new applications for valorizing agro-food waste need to be identified. Moreover, future studies on agro-food waste should not be limited to identifying their content of active compounds and their importance for human health, but should focus on exploiting these wastes as a profitable resource for obtaining high quality value-added food products.

Keywords: food waste management, resource efficiency, green technologies, nutritional supplements

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INTRODUCTION

The rapid growth of the global population and changes in lifestyle have led to a significant increase in the quantity of agro-food waste and secondary products. Nearly one-third of annually produced food is wasted, leading to severe reduction of natural resources (Liu et al., 2023) and which could feed 1.26 billion undernourished people. Agro-food waste, if not managed properly, can pose a serious threat to the environment and human health, while also being associated with significant losses of other resources, such as water, energy, and human effort.

In the context of the circular economy, it is necessary that the waste and secondary products resulting from the processing of agro-food production to be converted into useful ingredients for the food industry or for animal feed, due to the high content of bioactive compounds, but also to new processing technologies that limit damage caused by heat during drying.

Improper management of agro-food waste equates approximately 3.3 billion tons of carbon dioxide, equivalent or 4.4 kilotons of carbon each year, representing approximately 8% of total greenhouse gas emissions to the environment (Liu et al ., 2023). The utilization of this agro-food waste as a source of bioactive compounds in the food industry or in animal feed is a pioneering solution for reducing waste and generating new economic opportunities. This approach aims not only to reduce the environmental impact of agro-food waste but also to obtain new functional foods with high additional value and dietary supplements, as well as sources of income, thus fulfilling the principles of the circular economy. Furthermore, the valorization of agro-industrial waste and by-products facilitates the development of increasingly competitive, sustainable, and economically viable production systems.

The purpose of this review is to highlight the potential of agro-food waste and by-products as a source of bioactive compounds for the production of functional foods. Therefore, this study presents data from the literature regarding various sources of food waste, the content of bioactive compounds in agro-food waste and by-products, and their potential utilization in the food industry and animal feed as a source of bioactive compounds to obtain

high-value-added foods that meet the specific characteristics of functional foods.

THE CIRCULAR BIOECONOMY OF AGRO-FOOD PRODUCTION

The valorization of agro-food waste is an integral part of the concept of "zero waste economy," in which waste is transformed into valuable goods with practical applications, offering potential savings of natural resources and their sustainable use. In addition, the "Farm to Fork" concept also aims to integrate circular economy principles into food processing through environmentally friendly technologies. Achieving the "zero waste" goal and accelerating the transition of the food industry to a circular bioeconomy primarily relies on integrated value chains, where waste and by-products are used as raw materials to obtain value-added products.

Food waste and by-products could be utilized for developing new food ingredients or products for human consumption, promoting full valorization and reintegration into the food supply chain within the circular bioeconomy concept, thereby creating revenue streams as well as business opportunities and employment.

Agro-food wastes are secondary products that have no direct food value for humans, because the extraction and processing of the nutritional and biologically active compounds from them generates very high costs (Mnisi et al., 2022). Large amounts of agro-food waste are dumped in landfills, leading to environmental pollution (Mnisi et al., 2022). Thus, the recovery of agro-food waste in animal feed fits into the contemporary concept of circular bioeconomy also contributes to, sustainable development of animal production and ensuring food security by providing high quality food at affordable prices to the rapidly growing human population. In addition, it can be a strategy for enriching agro-food products of animal origin (eggs, meat, milk) into bioactive compounds with a role in promoting human health, but also an environmental protection strategy.

THE IMPACT OF AGRO-FOOD WASTE ON THE ENVIRONMENT

Agro-food waste represents a serious problem in the culture of sustainable consumption, with major implications for the environment. These wastes, resulting from any part of the food chain, have a significant impact on natural resources, biodiversity and the quality of the environment.

One of the main aspects of the impact of agro-food waste on the environment is related to soil pollution. Improperly disposed organic waste can contain harmful chemicals that seep into the soil, affecting its fertility and structure, thereby affecting local flora and fauna.

Also, agro-food waste can contribute to surface and ground water pollution. Disposing of waste near watercourses or in areas with groundwater can contaminate drinking water sources and affect the biodiversity and quality of aquatic habitats.

Another important aspect of the major impact of agro-food waste is related to greenhouse gas emissions. The process of decomposition of organic matter in waste generates significant emissions of methane and carbon dioxide, thus contributing to global warming and climate change.

THE ECONOMIC AND SOCIAL IMPLICATIONS OF AGRO-FOOD WASTE

According to the FAO (Food and Agriculture Organization), about one-third of all food produced in the world is lost or wasted, and about 690 million people, or almost 9% of the global population, suffer from chronic hunger. This means that these people do not have regular and sufficient access to nutritious and safe food to meet their basic nutritional needs.

According to Eurostat, in 2022, 95.3 million people in the EU (22% of the population) were at risk of poverty or social exclusion, lived in households facing at least one of the three risks of poverty and social exclusion. Correspondent to prognoses, by 2050 there will be 9.3 billion people on Earth. Ensuring an uninterrupted food supply with such population growth - even with the use of modern crop improvement technologies - will be an extremely difficult task. According to experts, providing people with safe food will also require a drastic reduction in food waste in the future, especially household losses (Bond et al. 2013, FAO 2014).

Surpluses occur at all levels of the food chain, however, we experience differences between developing and developed countries. Surpluses generated during agricultural production are more typical in economically underdeveloped countries than in industrialized countries. The main reasons are outdated harvesting technology, inadequate

storage, handling and transport procedures, inefficient infrastructure and lack of adequate knowledge.

By recycling or valorizing food waste, the negative impact of food waste could be reduced and the economic losses associated with it can be avoided. The valorization of agro-food waste can lead to increased economic efficiency by creating new employment opportunities and can stimulate innovation and research in the field of green technologies and the circular economy.

AGRO-FOOD WASTE AS A POTENTIAL SOURCE OF BIOACTIVE COMPOUNDS

As people become more aware of the relationship between nutrition and health, the food industry strives to develop new products enriched with nutritionally valuable ingredients such as dietary fiber, polyphenols, vitamin or minerals, which have a positive effect on human health.

Agro-industrial wastes and by-products are rich sources of macronutrients (carbohydrates, proteins and fats), micronutrients (vitamins, iron, calcium and potassium) and numerous bioactive compounds (Table 1). Bioactive compounds are natural substances that have the potential to influence positively human health. Most of the bioactive compounds, produced from the primary and secondary metabolism of the plant cell, have antioxidant, antimicrobial and anti-inflammatory effects; they have cardioprotective and neuroprotective properties, prevent obesity and regulate diabetes (Banwo et al., 2021). These compounds often exist in higher concentrations in discarded parts than in those considered marketable. The utilization of these bioactive compounds presents an opportunity to transform food waste into valuable resources.

Table 1

Bioactive compounds from food waste streams and by-products

Bioactive compounds	Food waste streams and by-products	References
Carbohydrates	Citrus fruits, apple pomace, potato peel, carrot.	Nayak et al., 2019.
Phenolic compound	White grape pomace, apple pomace, peel and pulp of orange, potato peel.	Hernandez et al., 2017; Thomas et al., 2019.
Flavonoids	Apple pomace, citrus peel, mango kernel, banana peel, beetroot, broccoli.	Vu et al., 2018; Hernandez et al., 2017; Vulic et al., 2014.
Anthocyanins, carotenoids, betalains, lycopene	Apple pomace, plum pomace, mango peel, carrot, banana peel, berries, beetroot, tomato pomace and peel.	Sojka et al., 2015; Vulic et al., 2014; Klavins et al., 2018.
Organic acids	Waste cheese whey, apple pomace, banana peel, citrus peel waste, fruit and vegetable waste, fruit and vegetable waste.	Piwowarek et al., 2016; Patsalou et al., 2017.
Essential fatty acids	Grape seeds, flaxseed waste and sesame seed hulls, hemp seed, camelina seed.	Dalmolin et al., 2010; Socaci et al., 2017; Mierlita et al., 2024.

Vegetables contain high levels of water, soluble carbohydrates, fiber, minerals, vitamins, polyphenols and other bioactive compounds. Often vegetables are considered waste once they undergo color changes, are infested with microbes, are broken or hit, or reach ripening (ripening) levels that make them unacceptable to consumers. This waste can occur at any point in the vegetable supply chain, from farm to consumer. Around 30% of vegetable production ends up being food waste, which is composted or incinerated, causing serious environmental problems, including toxic or greenhouse gas emissions and microbial proliferation, due to the high moisture content and leachate of waste.

Following the processing of the fruits by squeezing or crushing, in order to obtain the juice, the by-product is the pomace, which represents 20-40% of the weight of the fresh fruit (Mnisi et al., 2022). It contains part of the fruit pulp, peel and seeds. Annually, more than 500 million tons of pomes are produced globally (Hu et al., 2023), for which no unified

sustainable management strategy has been developed.

Phenolic compounds, carotenoids and dietary fibers are the most widespread bioactive compounds present in agro-food waste. They can find application in several industrial fields as functional components to promote the reuse and recycling of biomass but can also be used in animal feed (Socas-Rodríguez et al., 2021). These natural antioxidants, especially carotenoids and polyphenols, have anti-aging, anti-inflammatory, anti-viral, anti-microbial, anti-cancer agents and generally occur in citrus fruits and fruit pomace (including grape). Thus, these agro-food wastes can be used to improve the texture and color of products but also to improve the shelf life of food and beverages.

Agro-food waste has a high content of dietary fibers that affect human nutrition and health. They promote gastrointestinal peristalsis to alleviate constipation. In addition, they have a direct impact on the human digestive microflora, providing the energy and nutrients necessary for the proliferation of probiotics in the digestive tract.

The use of agro-food waste in the food industry

Some agro-food waste and especially fruit pomace (aronia, currants, blueberries, grapes, sea buckthorn) after treatments such as controlled drying and grinding could be used as ingredients with nutritional and functional value, in the food industry, with the aim of obtaining foods enriched in natural bioactive compounds. Food enrichment in antioxidants is important in reducing oxidative damage in consumers, having a critical role in protecting cellular components from the products resulting from the oxidative degradation of different compounds (Vrsanska et al., 2016). The increased interest in increasing the content of antioxidants in the human diet and implicitly in food is determined by the role that antioxidants have in the prevention of cancer, the aging process, cardiovascular and neurodegenerative diseases (Bohn, 2019).

The use of agro-food waste as a natural source of bioactive compounds in the food industry can reduce the need for synthetic food additives that can have a negative impact on the health of consumers therefore, enriching food with natural bioactive compounds could have a positive effect on the perception and acceptance of food by consumers.

Agro-food waste rich in bioactive compounds, such as over ripe berries, fruits unacceptable for marketing (with defects in size, shape, appearance), discarded peels, peels, fruit pomace resulting from the production of juices, after processing by appropriate methods can be used in the food industry as a source of natural food additives, thus replacing food additives of chemical synthesis.

Recent studies have highlighted the potential of polyphenol-rich olive waste as a natural antioxidant in minced meat, which protects lipids and proteins against oxidation, preserves a specific color of fresh meat and extends the shelf life of the product by up to three days (Muino et al., 2017). In addition, it has been found that apple peel extract protects proteins and lipids from trout during refrigeration, leading to a reduction in the level of peroxides that have negative effects on consumer health (Bitalebi et al., 2019).

Various bioactive compounds found in food waste have been identified as potential natural antimicrobial agents for food preservation. For example, olive leaf extract reduces bacterial contamination in leafy vegetables and shrimp. Studies have shown that pomegranate peel extract exhibits antibacterial effects against *S. aureus* and *B. cereus*, showing promising antibacterial effects in chicken (Kanatt et al., 2010).

Many of the colorants used in the food industry are synthetic, although some agro-food wastes and especially berry waste and pomace can be natural sources of colorants such as carotenoids and anthocyanins. These compounds could be used as natural colorants in products and help extend the shelf life of food and beverages by preventing pathogens, contaminants or unpleasant flavors.

Apple and citrus waste are significant sources of water-insoluble dietary fibers, such as pectin, which are beneficial for gut microbiota health. By extracting pectin, it can be utilized as a gelling agent in baking, confectionery, and meat products.

Most vegetable and fruit waste and by-products can be considered a source of protein and dietary fiber. For example, in addition to improving nutritional values, the inclusion of dried and ground potato peels in a proportion of 5% increased the strength and elasticity-extensibility of the dough (Ben Jeddou et al., 2017).

Waste resulting from fruit processing is a source of bioactive compounds (polyphenols,

flavonoids, vitamins, minerals) that can be reused to meet the requirements of the circular economy model (Piasecka et al., 2022). By isolating these bioactive compounds, innovative food products rich in natural bioactive compounds or dietary supplements can be developed, reducing waste and promoting sustainable production systems within the circular bioeconomy context. The development of healthier food products that are not only nourishing but also functionally beneficial involves the advancement of innovative food technologies. Contemporary lifestyles largely rely on highly processed foods with low nutritional value, thus enriching them with bioactive compounds has become a necessity.

The use of agro-food waste in animal feed

A significant issue in livestock production is the decline in feed resources. Therefore, the utilization of agro-food waste in animal feed represents new methods of sustainable development of food production, by using locally available, less competitive and cost-effective materials as feed ingredients.

Some of the agro-food waste and by-products can be safely used as animal feed without compromising the safety of animal-derived products and animal welfare. Currently, available processing technologies allow for the safe preservation and utilization of agro-food waste for animal feed, transforming them into value-added foods with high-quality nutrients. Agro-food waste processing methods include dehydration, ensiling, extrusion, granulation and treatment with probiotics (Cheraghi Saray et al., 2014).

Innovative feeding technologies based on the utilization of agro-food waste and by-products rich in bioactive compounds can reduce enteric methane and nitrogen emissions in ruminants, while simultaneously improving the nutritional composition and extending the shelf life of meat and meat products by enhancing their antioxidant capacity.

The edible oil processing industry generates waste, the most important of which are oilcakes and oilseed meals. These are by-products rich in proteins, but also in bioactive compounds (polyunsaturated fatty acids, antioxidants, sterols, carotenes). This waste is pre-treated and used to produce animal feed (Chang et al., 2018).

Agro-food waste is underutilized in the food industry for obtaining pectin, vitamins, polyphenols, flavors, and food pigments. Additionally, given that fruit and vegetable waste production is seasonal, it seems opportune to preserve them in dried form and then use them as feed ingredients for animal nutrition. Just like the vegetables and fruits that result, waste can be a highly valuable source of natural antioxidants like polyphenols (especially anthocyanins and flavonoids), carotenoids and vitamin E (Pieszka et al., 2015), some of which are found in higher quantities in waste than in products accepted by the market. Furthermore, these wastes contain unsaturated fatty acids, numerous vitamins and minerals, so their use as feed additives could enrich their diet in valuable bioactive components, which are efficiently transferred to agro-food products of animal origin.

This strategy of using vegetable and fruit waste in animal feed leads to obtaining foods (meat, milk, eggs) with high-added value, which can meet the specific characteristics of functional foods. The increased consumer interest in functional foods is due to their high content of high-quality proteins, vitamins, minerals, colorants, and natural antioxidants, phospholipids, and polyunsaturated fatty acids, which have positive effects on human health, improving immune functions and fertility (Hoffman et al., 2004), and also possess anti-inflammatory, antitumor, and antiviral properties (Wall et al., 2010).

CONCLUSIONS AND FUTURE PERSPECTIVES

Agro-food waste represents a significant source of bioactive compounds crucial for human and animal health. Thus, transforming this waste into high-value-added products is an optimal solution to reduce the burden of waste management, decrease resource and energy consumption, and protect the environment. New and innovative technologies for extracting bioactive compounds have been developed to enhance industrially processed foods or improve the quality of animal-derived foods (milk, meat, eggs) by incorporating these waste materials into animal diets. The utilization of these sustainable technologies offers various advantages, including waste reduction, the creation of new economic opportunities, promotion of circular economy principles, and the development of functional foods and nutritional supplements.

Despite the establishment of various technologies for the sustainable valorization of

agri-food waste, they have been successfully tested in research laboratories, while their implementation on a commercial scale presents challenges and limitations, requiring researchers to address these issues in future studies. Many of the technologies tested on a laboratory scale require excessive extraction costs, generated by expensive equipment, solvents used and high energy consumption, this is a significant obstacle to the use of bioactive compounds from agri-food waste as natural additives in the food industry. Additionally, challenges such as low extraction rates, lower stability of natural compounds compared to synthetic ones, and difficulties in managing the resulting waste residues, which may pose risks to the environment and human health, need to be addressed.

In this context, processing agri-food waste through appropriate methods and using them as a source of bioactive compounds in animal feed to obtain animal-derived foods (meat, milk, eggs) with high added value is an effective approach to sustainable valorization of these wastes on a commercial scale. Ultimately, the application of efficient sustainable valorization processes for agri-food waste by transforming them into high-value-added products can significantly contribute to promoting circular bioeconomy, effectively addressing the macro-global issue of environmental protection.

In conclusion, one of the main challenges for the future will be to improve the efficiency of extraction processes and develop new methods that are more environmentally friendly. Additionally, it is necessary to establish the bioavailability and safety of the extracted compounds, considering that agro-food waste from which they are extracted deteriorates rapidly and may contain various toxic chemicals from insecticides and pesticides used in agricultural production. Furthermore, new applications for valorizing agro-food waste need to be identified, the goal is to recycle and aim for 'zero waste; zero loss'. Finally, future studies on agro-food waste should not be limited to identifying their content of active compounds and their importance for human health but should focus on utilizing these wastes as a profitable resource for obtaining high-quality food products with added-value.

REFERENCES

Banwo, K., Olojede, A. O., Adesulu-Dahunsi, A. T., Verma, D. K., Thakur, M., & Tripathy, S., et al. (2021). Functional importance of bioactive compounds of foods with potential health benefits: A review on recent trends. Food Bioscience, 43, 101320. https://doi.org/10.1016/J.FBIO.2021.101320.

Ben Jeddou, K., Bouaziz, F., Zouari-Ellouzi, S., Chaari, F., Ellouz-Chaabouni, S., Ellouz-Ghorbel, R., & Nouri-Ellouz, O. (2017). Improvement of texture and sensory properties of cakes by addition of potato peel powder with high level of dietary fiber and protein. Food Chemistry, 217, 668–677. https://doi.org/10.1016/J.FOODCHEM.2016.08.081

Bond, M., Meacham, T., Bhunnoo, R. Benton, T. G. (2013): Food waste within global food systems.

Chang, F.C.; Tsai, M.J.; Ko, C.H. Agricultural waste derived fuel from oil meal and waste cooking oil. Environ. Sci. Pollut. Res., 2018, 25, 5223–5230.

Dalmolin, I.; M.A. Mazutti, E.A. Batista, M.A. Meireles and J.V. Oliveira (2010) Chemical characterization and phase behaviour of grape seed oil in compressed carbon dioxide and ethanol as co-solvent, J. Chem. Thermodyn., 42(6), 797–801, http://DOI:10.1016/j.jct.2010.02.003

FAO - Global Food Losses and Food Waste – Extent, Causes and Prevention. Roma: FAO ONU, 2011, https://ec.europa.eu/eurostat/web/income-and-living-conditions/database?node_code=ilc_pe, (Accessed 09.04.2024)

Klavins L., Kviesis J., Nakurte I, Klavins M. (2018). Berry press residues as a valuable source of polyphenolics: Extraction optimisation and analysis. LWT, 93, 583-591.

Liu, Z.; de Souza, T.S.P.; Holland, B.; Dunshea, F.; Barrow, C.; Suleria, H.A.R. Valorization of Food Waste to Produce Value-Added Products Based on its Bioactive Compounds. Processes 2023, 11, 840. https://doi.org/10.3390/pr11030840.

Matei. E., Râpă M., Predescu A., Țurcanu A., Vidu R., Predescu C., Bobirica C., Bobirica L., Orbeci C. (2021) - Valorization of Agri-Food Wastes as Sustainable Eco-Materials for Wastewater Treatment: Current State and New Perspectives.

Mierlita, D.; Teusdea, A.C.; Matei, M.; Pascal, C.; Simeanu, D.; Pop, I.M. (2024) Effect of Dietary Incorporation of Hemp Seeds Alone or with Dried Fruit Pomace on Laying Hens' Performance and on Lipid Composition and Oxidation Status of Egg Yolks. Animals, 14, 750. https://doi.org/10.3390/ani14050750.

Mnisi CM, Mhlongo G and Manyeula F (2022) Fruit Pomaces as Functional Ingredients in Poultry Nutrition: A Review. Front. Anim. Sci. 3:883988. http://doi:10.3389/fanim.2022.883988

Muíño I., Teresa Díaz M., Apeleo E., Pérez-Santaescolástica C., Rivas-Cañedo A., Pérez C., Cañeque V., Lauzurica S., de la Fuente J. (2017). Valorisation of an extract from olive oil waste as a natural antioxidant for reducing meat waste resulting from oxidative processes. Journal of Cleaner Production, 140 (2), 924-932. https://doi.org/10.1016/j.jclepro.2016.06.175 .

Nayak A. and B. Bhushan (2019). An overview of the recent trends on the waste valorization techniques for food wastes, J. Environ. Manage.,

233, 352–370, http://DOI:10.1016/j.jenvman.2018.12.041

Patsalou, M.; K.K. Menikea, E. Makri, M.I. Vasquez, C. Drouza and M. Koutinas (2017) Development of a citrus peelbased biorefynery strategy for the production of succinic acid, J. Clean. Prod., 2017, 166, 706–716, http://doi:10.1016/j.jclepro.2017.08.039

Piwowarek, K.; Lipiska, E.; Ha-Szymaczuk, E. (2016) Possibility of using apple pomaces in the process of propionic-acetic fermentation. Electronic Journal of Biotechnology, vol. 23, 1-6. https://doi.org/10.1016/j.ejbt.2016.07.004.

Socaci, S. A., Fărcaş, A. C., Diaconeasa, Z. M., Vodnar, D. C., Rusu, B., & Tofană, M. (2018). Influence of the extraction solvent on phenolic content, antioxidant, antimicrobial and antimutagenic activities of brewers' spent grain. Journal of Cereal Science, 80, 180–187. https://doi.org/10.1016/J.JCS.2018.03.006.

Socas-Rodríguez, B., Álvarez-Rivera, G., Valdés, A., Ibáñez, E., & Cifuentes, A. (2021). Food by-products and food wastes: Are they safe enough for their valorization? Trends in Food Science & Technology, 114, 133–147. https://doi.org/10.1016/J.TIFS.2021.05.002.

Vulic, J.J., Cebovic, J.M., Canadanovic-Brunet, G.S. Cetkovic, V.M. Canadanovic, S.M. Djilas and V.T. Tumbas Saponjac (2014) In vivo and in vitro antioxidant effects of beetroot pomace extracts, J. Funct. Foods, 6, 168–175, http://DOI:10.1016/j.jff.2013.10.003.