Agri-food by-products as a source of sustainable ingredients for the production of functional foods and nutraceuticals

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Abstract

The disposal of waste generated in the agri-food industry is one of the greatest challenges in achieving sustainable development. Although agri-food residues are a potential source of bioactive compounds with proven health benefits, they are largely unused and disposed of as organic waste. The recovery of bioactive compounds from agri-food waste to obtain products with high biological value, such as functional foods and nutraceuticals, is an idea that stems from the concept of bioeconomy and combines environmental issues with economically viable production. Some of the main agri-food wastes in Serbia that have the potential to be recycled into value-added products are apple, plum, grape, tomato, and beet pomace, and oilseed cakes. Bioactive compounds isolated from these wastes include polyphenols, fibers, essential fatty acids, minerals, various volatiles and pigments. This article focuses on the most common food wastes and the potential reuse of these undervalued material to produce value-added products such as functional foods, nutraceuticals or food additives.

Key words: agri-food by-products, bioactive compounds, functional foods, nutraceuticals

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Introduction

Food production is constantly increasing to meet the needs of the growing population on earth. At the same time, the agri-food industry generates greater amounts of waste every year. According to a report by FAOSTAT (Food and Agriculture Organisation Corporate Statistical Database), one third of all food produced worldwide is wasted or lost. The largest share is in the fruit, vegetable and sea food industry (1).

Sustainability in agri-food industry

In recent years, the concept of sustainability, together with the growing concern for the protection of the environment, has gained much attention at the global level. European countries have committed to achieving the food loss and waste reduction targets adopted by the United Nations General Assembly as part of the 2030 Agenda for Sustainable Development (2). In 2016, the EU established the Platform on Food Loss and Food Waste and proposed to "use all relevant research and innovation activities and financial instruments to support the development and implementation of innovations in the food supply chain to prevent food loss and food waste, with a further focus on primary production with the aim of transforming discarded materials into new value-added products" (3). Food losses and waste also have an impact on climate change as they leave a significant greenhouse gas footprint. The agri-food industry generates significant CO_2 emissions, and when food ends up in landfills, this promotes methane production, an even more potent greenhouse gas. One of the Sustainable Development Goals is therefore to halve global food waste and reduce food losses in production and delivery by 2030 (4).

In 2018, the National Alliance for Local Economic Development (NALED) launched the "Towards Better Food Waste Management" project in the Republic of Serbia to improve the management of this type of waste, create legal solutions and regulate bio-waste flows (5). Regarding food waste and losses, Serbia is just beginning to systematically investigate this problem and identify the possibilities for its solution. In its publication "Roadmap to the circular economy 2020", the Serbian Ministry of Environmental Protection highlighted the agri-food industry as a promising area for the circular economy, stating that although there are no accurate data on food waste and loss for Serbia, it is important as an indicator of the success of the transition from the linear economy of "produce-use-throw-away" to a reuse or circular policy (6). This article addresses the most common food wastes and the potential reuse of undervalued material to produce value-added products such as functional foods, nutraceuticals or food additives.

Waste management

The disposal of waste generated in the agri-food industry is one of the greatest challenges in achieving sustainable development goals. Residues from the processing of fruit and vegetables (usually peels and seeds) contain mainly carbohydrates (cellulose, pectin, starch) and a small amount of protein and fat by dry weight (7).

The chemical complexity and high moisture content of the waste, among other factors, make it difficult to fully utilise the waste. There are considerable variations in the chemical composition as well as in the pH value of the pomace. In general, the composition of the waste produced in the agri-food industry depends on the processing procedures and seasonal variations. Residues have a high water content, which could be associated with bacterial contamination. Nowadays, the by-products are usually processed into animal feed and agricultural compost. However, there are many ways to recycle food waste. Plant-based waste has a high potential and is a renewable energy source due to its high cellulose and lignin content. Cellulose and hemicellulose are enzymatically degraded, releasing glucose and xylose, which can be easily converted into ethanol by fermentative microorganisms. Lignin, on the other hand, yields hydrogen and methane after pyrolysis and aerobic degradation. Moreover, this pathway leads to the production of enzymes and bioplastics. Furthermore, anaerobic digestion of waste leads to the production of electricity, heat and biofertiliser. Incineration is one method of obtaining hydrogels. Finally, the most promising approach to waste management is the use of by-products as raw materials to obtain various compounds that can be used as food supplements, fortifiers, cosmetic ingredients, food colouring and preservatives (8).

The use of plant food waste to obtain products with high biological value is an idea that stems from the concept of sustainability and combines environmental issues with economically viable production.

Biopotential of agri-food industry waste

Bioactive compounds isolated from plant-based food waste include polyphenols, vitamins A and E, peptides, essential fatty acids, fibers, minerals, various volatiles and pigments (9).

Some of the most important plant-based food wastes are pomaces derived from apples, plums, grapes, tomatoes, beets, potatoes, and olives. There are no official reports on the amount of waste generated by the food processing industries, but it is estimated to be in the millions of tonnes annually (10). In general, fruit waste has great potential due to its high concentration of polyphenols. In addition, apple pomace is rich in pectin, which acts as a prebiotic and hypocholesterolemic agent (11). Tomato waste contains phenolic compounds as well as significant amounts of lycopene and carotenoids. Beet pomace contains significant amounts of betalains (betanin and isobetanin), while potato pomace contains glycoalkaloids such as chaconine and solanine, which have the potential to induce apoptosis in cancer cells (12, 13). In addition, oilseed cakes left over after oil extraction are rich in proteins, nitrogen and minerals and can be used for human consumption, especially as a supplement to existing, less sustainable protein sources (14).

Agri-food industry in Serbia

In Serbia, agri-food industry is the most important sector of the economy. According to the 2019 Food and Agriculture Organisation Corporate Statistical Database (FAOSTAT) data (1), agricultural crops cover more than one-third of the total land area.

Serbia is a well-known producer of high-quality fruit and vegetables (raspberries, apples, plums, grapes, cherries, potatoes, peppers, onions, tomatoes and carrots). Hence, the agri-food industry is of vital importance to the domestic economy. It is one of the few sectors of the Serbian industry that has increased its share in recent decades. In 2017, for example, food accounted for 10.3% of total Serbian exports (15). Nevertheless, waste management in our country faces numerous problems and the waste generated in the agri-food industry is still insufficiently utilised.

Sustainable ingredients of agri-food industry waste

Proteins

The intake of foods rich in proteins of animal or vegetable origin (e.g. meat, pulses and cereals) is essential for health, as they provide essential amino acids necessary for the growth, development and maintenance of numerous functions in the body. As the world's population continues to grow, so does the demand for food, especially that rich in protein. It is expected that up to 7 million tonnes of protein ingredients will be needed for human consumption by 2025 (16). Conversely, meat consumption must be halved in the coming decades if the Sustainable Development Goals are to be achieved by 2030. Therefore, this necessity for proteins should be met from plant-based and other alternative sources of protein (16). However, in recent years, several studies have highlighted the negative environmental impacts of intensive production not only of meat, but also of plant protein sources, manifested in increased global consumption of drinking water, alteration of biodiversity and chemical pollution. In addition, every kg of protein lost from animal or plant foods that ends up as waste generates between 15 and 750 kg of CO_2, additionally increasing the carbon footprint (17).

Food waste could be a significant source of protein which can be effectively upgraded by reintroducing it into the food chain as an ingredient or value-added product, for both animal and human consumption (18). Proteins from animal and plant-based waste may differ in terms of protein digestibility and nutritional value. To be considered a valuable source of protein, food waste should fulfill several conditions: it should have a high protein content, contain high-quality proteins with a balanced composition of essential amino acids and not contain toxic or allergenic substances (19).

Protein rich plant-based food waste is mainly generated in the production of vegetable oils, with about 364 million tonnes of by-products produced annually in the form of oil cakes (17). Depending on the type of vegetable waste, the cakes remaining after oil extraction can contain up to 50% of protein. Examples of significant protein sources include rapeseed and soybean oil cakes, with the soybean cake containing up to 27% highly digestible proteins and with an amino acid profile similar to an animal protein source. Protein isolates (>90% protein), protein concentrates (up to 80% protein) and protein hydrolysates can be prepared from these protein rich oil cakes (14). In addition, there is potential for protein recovery from by-products of other industries, including brewery spent grains, coffee and tea residues and various other plant wastes (19).

Although different ways of upgrading these by-products have been proposed, they are still mainly used as animal feed or end up as organic waste, due to the presence of various antinutritive compounds. They need to undergo appropriate pre-treatment and purification steps if they are intended to be included in human diets (17).

Animal-based food wastes, such as organs, bones, pieces of meat, blood and fatty tissue, are rich in lipids, carbohydrates and proteins. Proteins derived from these wastes can not only provide raw materials for lower cost products, but also enable a rational and sustainable use of resources while reducing waste that pollutes the environment (20).

The main protein sources among animal-based food waste are whey, collagen and keratin. Liquid whey is currently the most widely used source of protein and is a common food ingredient, especially in dietary supplements for athletes. Collagen and keratin from meat are cheap substrates for the synthesis of materials that can be used in biomedicine, especially in the production of nutraceuticals. Collagen is usually extracted and processed into hydrolyzed collagen, which is a source of bioactive peptides. These short amino acid sequences exert various biologically significant effects. Due to their ability to increase the hydration and elasticity of the skin, bioactive peptides from collagen hydrolysates find their application in the cosmetic and pharmaceutical industries. As components of food supplements, they are used to stimulate the production of new collagen and as part of anti-ageing medicine (20, 21).

Dietary fibers

A clear definition of dietary fiber is still debated by many researchers, but it is most commonly defined as inedible plant parts or analogous carbohydrates that are not digested or absorbed in the human small intestine and are fermented, fully or partially, in the large intestine. Dietary fibers include polysaccharides, oligosaccharides, lignin and related plant substances (22).

The properties of dietary fibers depend mainly on their primary chemical composition and structure, which are consequently related to the source from which the fibers are obtained and the method of their preparation. Basically, they are divided into soluble (pectins, gums, mucilages) and insoluble fibers (cellulose, lignin, some hemicellulose polymers). In the case of soluble fibers, their beneficial physiological effects could be directed towards cardiometabolic health (hypoglycaemic and hypocholesterolaemic activities), while the gastrointestinal benefits (laxative properties) are associated with insoluble fibers (23).

Food waste is becoming increasingly important as a source of dietary fiber because it is presented in the parts of plants that are often thrown away, such as peels, stems, leaves and pomace. Therefore, large quantities of pomace, that mostly come from the juice and wine industry, are one of the cheapest sources of dietary fiber. A study conducted by Sahni and Shere (2018) found that apple, carrot and beetroot pomace powders had a high crude fiber content of 21.51%, 17.94% and 11.12%, respectively (24). Extracted dietary fibers in powder form have several properties, such as low fat content, low caloric value, neutral taste and aroma, making them very satisfactory food ingredients that can influence both the physiological properties and sensory characteristics of certain foods (25). Indeed, dietary fibers represent multifunctional ingredients, as they often fulfil several functions in a food product, such as: nutritional quality and health promotion; ensuring the desired structure (e.g. porosity); sensory properties (texture, mouthfeel and freshness), physical characteristics (e.g. viscosity, density), and technological properties (e.g. the ability to bind water, emulsifying properties) (26).

Traditionally, cereals have been the main source of dietary fibers in food. However, a fiber derived from fruit and vegetable pomace offers several advantages over fiber from cereals. Fruit pomace provides high-quality total and soluble dietary fibers, as well as good functional properties such as water and oil binding capacity and gel formation. In addition, fiber derived from fruit pomace has a low caloric value, good fermentability in the large intestine and a lower content of antinutritive compounds than cereal products (24, 27).

In addition, dietary fibers from fruit pomace tend to be richer in soluble fiber than cereals. This is because soluble fibre is associated with benefits such as lowering blood cholesterol levels and inhibiting glucose uptake in the gut, which may be beneficial for overall health. An assessment of total, soluble, and insoluble fiber content of fruit juice pomaces (mango, guava, apple, orange, pineapple; in descending order) revealed their potential as a valuable source of dietary fibers (28). Therefore, there is a growing demand for distinctive dietary fiber ingredients, and fibers derived from fruit and vegetable waste apparently hold promising prospects as both novel ingredients in the market and for supplementation of food products.

Polyphenols

Polyphenols are the most abundant biologically active compounds. Given the diversity of their chemical structures, there are many classifications. In general, polyphenols are divided into two groups: flavonoids and phenolic acids. Flavonoids can be divided into several classes, i.e., flavones, flavonols, flavanones, dihydroflavonols, anthocyanins, isoflavonoids, etc. Hydroxybenzoic and hydroxycinnamic acids are the main classes of phenolic acids (29).

Polyphenols are characterized by a number of different biological activities, mainly due to their structure. Many studies have shown that these compounds can act as potent anti-inflammatory, anti-cancer and anti-microbial agents due to their antioxidant properties (30).

Plant-based waste produced by the agri-food industry is a rich source of phenolic compounds. For example, apple pomace has been found to contain flavonoids such as isorhamnetin, kaempferol, quercetin, procyanidin B2 and epicatechin in extremely high quantities. Dihydrochalcones (phlorizin and phloretein), phenolic acids (p-coumaric, sinapic, caffeic, chlorogenic, *p*-coumaroylquinic acids, and ferulic) and anthocyanins (cyanidin-3-O-galactoside) have also been quantified (31). These compounds have anti-inflammatory, antimicrobial and antitumour effects. In addition, dihydrochalcones act as antidiabetics and can potential treat obesity and promote bone formation (32, 33).

Plum pomace is composed of peel and pulp, and these parts of the fruit were found to be effective against many chronic diseases due to the presence of bioactive compounds such as neochlorogenic and chlorogenic acid, quercetin and kaempferol (34).

Polyphenols from grape pomace (seeds, skins and stems) belong to the flavan-3-ols, flavonols, proanthocyanidins and anthocyanins. Numerous studies have confirmed that grape marc, especially the proanthocyanidins present, have antioxidant, anti-inflammatory, antimutagenic and anticarcinogenic effects (35). Raspberry pomace is rich in ellagic acid and ellagitannins (36).

Potato peel, a by-product of the manufacture of crisps, chips and other potato-based snacks, contains much greater amounts of polyphenols than the flesh (with dominant phenolic acids) (37). Polyphenols are also present in carrot and beet pomace, although these wastes are mainly valued for other bioactive compounds, such as soluble and insoluble dietary fibers and pigments (carotenoids and betalains).

Polyphenols from wastes are used for various applications: in the development of functional foods and for the production of food supplements (38). Some phenolics, e.g, anthocyanins, are natural colourants in food matrices (39).

Phytosterols

Phytosterols are triterpenoids, tetracyclic compounds found in plant foods, structurally similar to cholesterol. The highest concentrations of phytosterols are present in the unsaponifiable part of vegetable oils. Nuts, whole grain products and pulses are also good sources of phytosterols. The most abundant phytosterols are β-sitosterol, campesterol and stigmasterol (40). These cholesterol-like bioactive compounds have a low-density lipoprotein (LDL)-cholesterol-lowering effect by reducing cholesterol absorption in humans and thus preventing coronary heart disease (41). In addition, recent epidemiological and clinical studies have shown that plant sterols may have anti-inflammatory, antioxidant and anti-cancer effects (42). The estimated dietary intake of phytosterols is between 100 and 400 mg/day (43). However, the European Food Safety Agency (EFSA) has approved a health claim for plant sterols/stanol esters, stating that their daily intake of 1.5-2.4 g contributes to lowering blood cholesterol levels (44). Since it is not possible to consume such a high daily dose of phytosterols in a regular diet, they are widely used as ingredients in functional foods. A variety of foods with added phytosterols, such as margarine and dairy products, are currently available on the European market (45).

Industrial vegetable by-products such as cauliflower and broccoli (currently useless food waste with a waste rate up to 60-75% of raw materials), seeds and seed-containing press residues (especially rapeseed and soybean oil cakes), and by-products from the processing of fruits such as apples and berries have recently attracted much attention as potential sources of plant sterols, alongside other bioactive compounds. Therefore, these by-products could have a possible added value for the preparation of functional foods and food supplements that could be useful in the prevention and treatment of cardiovascular diseases (42, 44, 46, 47).

Carotenoids

Carotenoids, fat-soluble pigments, comprise a group of different compounds found mainly in vegetables, fruits, algae and some bacteria. There are several hundred carotenoids in nature, but only one hundred are present in the human diet (48). Considering their structure, they are divided into two main classes: carotenes, which contain carbon and hydrogen and are either cyclic (such as α-carotene and β-carotene) or linear (lycopene), and xanthophylls, which have at least one oxygen atom (such as lutein, zeaxanthin and β-cryptoxanthin). Furthermore, carotenoids can be divided into those with provitamin A activity (β-carotene and β-cryptoxanthin) and those without provitamin A activity (lycopene and lutein) (49).

Carotenoids have been used for centuries as natural colorants in many types of foods, beverages, dietary supplements and pharmaceuticals. In recent decades, research interest has focused on their use as bioactive compounds in human nutrition and health. The consumption of carotenoids has several beneficial effects, such as reducing the risk of cardiovascular disease, macular degeneration, diabetes, and liver disease, as well as inhibiting certain enzymes involved in the development of cancer (49, 50). Although carotenoids cannot be synthesized in the human body, there are no recommendations for their daily intake.

Plant-based waste can be a valuable source of carotenoids, containing similar or even higher concentrations of these antioxidant compounds than fruit and vegetables (51). Literature data indicate that the highest levels of carotenoids could be found in tomato by-products. The lycopene content in tomato peel by-products accounts for up to 90% of the total carotenoids; however, in the tomato seeds, β-carotene is the most important carotenoid (51). Tomato peels contain the highest lycopene content (approx. 377 μg/g), almost five times more than tomato paste, calculated on a dry weight basis (52).

Using tomato by-product extracts in the meat industry improves nutritional quality, reduces lipid oxidation and extends product shelf life (53). Furthermore, lycopene oil extracted from tomato peel waste has been shown to provide proper sensorial characteristics, meltability and antioxidant activity in reformulated cheese (54). Natural lycopene is also used in the bakery industry to improve the antioxidant capacity, colour and sensory properties of cakes and biscuits (55).

Oliveira et al. used lycopene from melon pulp in yogurt and soy beverages, achieving organoleptic properties equivalent to products available on the market (56). Regarding carrot by-products, the use of recovered β-carotene in meal replacement bars can reach the amount of provitamin A needed by humans (57).

Potential of agri-food by-products for different food products development

Agro-food by-products in the form of powders or extracts can be added to various foods, such as bakery products (bread, biscuits, cakes, etc.), dairy products (yoghurt, cheese, etc.), beverages and animal products (sausages) to increase the nutritional and functional characteristics of the products (58). In addition to their potential role as functional ingredients, agri-food by-products can also be used as natural food additives in the food industry to extend the shelf life of products, improve nutritional value or achieve a specific technological objective (improving physico-chemical and sensory properties), and thus have broad positive effects on consumer health (59). Nowadays, the public prefers natural foods without synthetic additives due to possible carcinogenic and allergenic effects. Therefore, there is an increasing interest in biologically active substances isolated from natural agri-food by-products, which can be an alternative to synthetic substances (60). Table I provides examples of some food products developed from various by-products.

Table I Examples of some food products developed from various agri-food by-products

Tabela I Primeri prehrambenih proizvoda napravljenih od nusproizvoda agro-industrije

By-product	**Added amount**	**Value-added product**	**Reported functional improvements**	**References**
 Raspberry pomace	25 and 50 % crumbled and non-crumbled raspberry pomace instead of wheat flour type 550	Cookies	Rich in antioxidant, dietary fibers, mainly cellulose, and lignin, minerals, without negative influence on organoleptic characteristics	(59)
 Apple pomace	2, 4, 6, and 8 % apple pomace replacing lean meat	Buffalo meat sausages	Improved physicochemical and sensory properties	(61)
 Grape pomace	Grape skin flours, 60 g/kg	Yogurt	Higher total phenolic content and antioxidant activity, lower pH, fat content, and syneresis, as well as textural quality compared to control.	(60)
 Potato peel	Extracted potato fiber at 0.4 % on a flour basis	Bread	Improved physicochemical properties (softer texture and bread staling reduction)	(62)
 Tomato peel	Extracted carotenoids at concentrations of 1-5 %	Ice-cream	Increased antioxidant activities and sensory properties (flavor, texture, melting quality, and color)	(63)
 Red pepper waste	Freeze-dried encapsulated waste, 10 % (w/v)	Yogurt	Better physicochemical properties (improved solubility, flowing and color) and increased number of lactic acid bacteria	(64)

Conclusion

Considering the amount and biopotential of waste generated in the agri-food industry, there is an obvious need to convert the present bioactive compounds into valuable products, thus maintaining ecological balance and contributing to more sustainable agricultural production. The reused compounds may have benefits in the food industry as natural colourants, antioxidants, value-added ingredients, or as engaging substances in pharmaceutical and cosmetic products.

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Nusproizvodi agro-industrije kao izvor održivih sastojaka za proizvodnju funkcionalne hrane i nutraceutika

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Kratak sadržaj

Odlaganje otpada koji nastaje u prehrambenoj industriji jedan je od najvećih izazova u postizanju održivog razvoja. Iako su nusproizvodi koji nastaju u prehrambenoj industriji potencijalni izvor bioaktivnih jedinjenja sa dokazanim pozitivnim zdravstvenim efektima, oni se uglavnom odlažu kao organski otpad. Iskorišćenje bioaktivnih jedinjenja iz ovih nusproizvoda u cilju dobijanja proizvoda sa dodatom nutritivnom i biološkom vrednošću, kao što su funkcionalna hrana i nutraceutici, ideja je koja proizilazi iz koncepta bioekonomije i kombinuje ekološki aspekt sa ekonomski održivom proizvodnjom. Neki od glavnih nusproizvoda koji se generišu u Srbiji sa potencijalom da se iskoriste u proizvodnji proizvoda sa dodatom vrednošću su trop jabuke, trop šljive, komina grožđa, trop paradajza, uljane pogače i dr. Bioaktivna jedinjenja izolovana iz ovih otpada uključuju polifenole, peptide, vlakna, esencijalne masne kiseline, minerale, različite isparljive materije i pigmente. Ovaj članak se fokusira na najčešće otpade prehrambene industrije i potencijalnu ponovnu upotrebu ovog još uvek neiskorišćenog otpadnog materijala za proizvodnju proizvoda sa dodatom vrednošću kao što su funkcionalna hrana, nutraceutici ili aditivi.

Ključne reči: nusproizvodi agro-industrije, biolološki aktivna jedinjenja, funkcionalna hrana, nutraceutici