



Reuse of fruits and vegetables biowaste for sustainable development of natural ingredients

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ABSTRACT

Considering the annual waste in the food sector that occurs throughout the value chain, it is important to establish strategic measures to reduce, value and reintroduce them into the industrial sector. Additionally, the constant search for the development of sustainable strategies to promote safe and healthy products for consumers has gained great prominence. Biowastes from fruits and vegetables present in their composition an excellent source of compounds of interest, which can be reused in different technological routes, providing added value in the industrial, socioeconomic and therapeutic sectors. In particular, the phenolic compounds present in fruit and vegetable biowastes, have bioactive and preservative characteristics that are excellent candidates for the development of natural ingredients that can be substitutes for synthetic preservatives. As the list of identified phenolic compounds is extensive and accessible, the interest in these compounds is gaining more and more prominence, since the use of ingredients of synthetic origin is being delayed by actions harmful to the health of the consumer. Phenolic compounds, in addition to having preservative capacity, such as antioxidant and anti-microbial capacity, are also known for their anti-inflammatory, anticancer, antidiabetic, antiallergic and other biological properties, which increases the interest in their use in functional and nutraceutical preparations. Based on this, this review gathers information on the impacts that the exacerbated generation of fruit and vegetable waste can generate in the environmental, economic and social sectors, as well as lists different ways of reusing these wastes, highlighting the characteristics of phenolic compounds.

1. Biowaste from the agro-industrial sector

The agri-food industry is one of the sectors with high production of waste, resulting from processing or losses in the production chain. The use of agro-industrial biowaste represents an advantageous opportunity in the development of by-products, as well as in the aggregation of lost value, through its sustainable use of these wastes (Egea et al., 2018).

Food disposal worldwide reaches about a third of food production with fruit and vegetable waste the predominant. The biggest problem involving the generation of fruit and vegetable biowastes is related to their high moisture content and organic load that makes them susceptible to microbial contamination, bringing difficulties in handling and treatment, and causing a significant negative impact on the environment (Ramos-Andrés et al., 2021).

Biowaste from fruit and vegetable processing is still underexplored at a commercial level, even being rich in dietary fibers and bioactive compounds with biological importance (Majumder & Annegowda, 2021). The most convenient way to eliminate bio-waste is to reuse it in the production of animal feed, organic fertilizers, or, in some cases, for burning, dumping in the environment and sanitary landfills. The non-reuse of these industrial surpluses, in addition to the aggressive impacts that causes on the environment, also result in a great loss of nutrients with great potential for several industrial sectors. Therefore, it becomes increasingly urgent to create strategies to explore new management routes, in order to take advantage of all those biowaste (Khorairi et al., 2021).

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1.1. Provenance and worldwide production

The food loss is one of the main responsible for the generation of waste on the planet. A report published by the United Nations Food and Agriculture Organization (FAO, 2019), show that 14% of all food produced is lost during the harvest process until it reaches retail. At retail and by consumers, the losses reach 17% as published by the UNEP's Food Waste Index Report (Forbes et al., 2021), resulting in a very significant amount.

Biowaste is the commonly used term for food loss and waste (Raak et al., 2017), being defined as the amount of food that is discarded from the food supply chain. Losses regard the biowaste generated in the first stages of the food chain, more specifically in the production, harvest, up to processing. While the concept of waste is more related of the food discarded at the end of the food chain, comprehending retail and final consumption (FAO, 2019).

Globally, considering the stages of the food supply chain, the losses and wastes in production phase are usually caused by inadequate practices of harvesting, management of food, and by climatic changes caused naturally in the field. In the storage, the losses occur due to inappropriate practices and incorrect management for each product, without considering their shelf life. In food transport, losses occur due to poorly planned logistics, and, in the processing, it is related to a lack of employee training and old and malfunctioning equipment. In the retail phase, losses occur due to the limited shelf life of products or for they do not meet the aesthetic standards established by consumers. Finally, the consumers generate large amount of biowaste due to lack of planning at the time of purchases, failure to identify expiration dates and misconduct in storage (FAO, 2019).

In the FUSION study (Stenmarck et al., 2016), supported by the European Commission, was estimated the amount of food waste generated at each stage of production. Thought this study, it was possible to identify the final consumer as the responsible for the largest fraction of biowaste generation (53%), followed by 19% in processing, 12% in food service, 11% in production and 5% in wholesale and retail, considering edible and inedible parts of food.

As reviewed by Klai et al. (2021), the losses resulting from the processing of fruits and vegetables were the most outstanding, representing between 15% and 20% of the total waste generated in the agroindustry. This information corroborated with the data presented by FAO (2019), which stated that the loss of fruits and vegetables was equivalent to 21% of the total waste generated in 2016. In addition, in terms of values, according to a study published by FAOSTAT (2022a), between 2010 and 2019 the losses caused during the storage and transport of fruits and vegetables for human consumption were, worldwide, around 20 million tons of fruits and 80 million tons of vegetables.

In 2019, the last year considered in the food balance, worldwide losses were approximately 22 million tons of fruit and 83 million tons of vegetables (FAOSTAT, 2022a). In this way, it is possible to observe that the amount of waste has been increasing with each passing year, and it may be that in 2020 the generation was equivalent or greater, since the production of fruits and vegetables was similar to 2019, with about 887 million and 1.1 billion tons (FAOSTAT, 2022b).

1.2. Negative social, environmental and economic impact

With the increase in population, an increasing demand for food is estimated worldwide, requiring the development of techniques and strategies to minimize food waste throughout its production chain (Mattsson et al., 2018). The scarcity of resources, the loss of food and the generation of waste throughout the production and supply chain affect the agri-food sector, in its social, economic and environmental spheres (Agnusdei et al., 2022).

Regarding the social impact, food waste includes the global food security and the millions of people that currently suffer from food shortages and malnutrition (Mattsson et al., 2018). In the year 2020, it

was estimated that between 720 and 811 million people went hungry, with more than 118 million people than estimated in 2019. In addition, about 2.37 billion people did not have access to safe food (FAO, 2019). On the other hand, in developed and high-income countries, billions of tons of quality food are discarded (Teigiserova et al., 2020).

In the environmental field, agro-industrial production is the sector that most uses natural resources for its development. There is consumption of about 70% of drinking water, soil degradation, high energy consumption and interference in water quality by the addition of fertilizers to the soil, in addition to the emission of about 30% of greenhouse gas emissions (Bell et al., 2018). About 77% of total agricultural land is destined for the production of food for human consumption, and approximately 23% results in losses. Losses from fruit and vegetable crops represent about 19% and 30% of this territory (Kummu et al., 2012).

In a study published by FAO (2019), the cultivation of fruits and vegetables has great responsibility in the environmental sector, since it has a carbon footprint of 7% and a freshwater footprint of 14%.

Current food consumption habits, where the demand for products that are easy to access and consumption has become popular, was increasing the demand for high quality and safe processed foods for consumption. With this, the mass processing of food generates an exacerbated amount of biodegradable biowaste that need adequate attention to minimize the associated problems (Simões et al., 2021). Transport for the relocation of these biowaste has a high associated cost for industries, in addition to a negative impact on the environment due to its inadequate management (Klai et al., 2021).

Agro-industrial waste has in its composition a matrix rich in compounds of interest, which can be recovered, bioconverted and reintroduced into the production chain again, which can contribute to the economic sector (Ng et al., 2020). The reintroduction of these raw materials in the industrial sector, as well as their processing to obtain products with great economic potential, lead to the realization of the concept of a circular bioeconomy, whose reduction, reuse and recycling are introduced into the waste management system, creating a cycle to assign an economic level to waste, which is commonly wasted (Klai et al., 2021).

The introduction of a circular bioeconomy can lead to the reuse of agro-industrial waste as a resource for the sustainable production of biomass; a systemic approach can be incorporated so that the reduction of food losses is minimized and the supply of safe and sustainable food occurs; it can reduce CO₂ emissions and the use of non-renewable resources; can encourage consumers to reduce food waste through sustainable consumption patterns, such as incorporating products with a lower environmental footprint; it can generate new jobs and consolidate great economic, sustainable impact and less dependence on non-renewable resources (Bell et al., 2018).

The action plan proposed by European countries introduced food waste in a circular bioeconomy as a priority, where obtaining value-added products in biorefineries is addressed as a potential strategy to replace the use of unprocessed resources (Jiménez-Moreno et al., 2020). Obtaining products from biological resources has been growing year after year. The European Union estimates a growth of around 50 billion euros in market value by the year 2030 (Bell et al., 2018).

With the objective of guaranteeing food security for the entire population, reducing food waste, preserving soils and reducing greenhouse gas emissions, the ONU (2015) launched the 2030 Agenda, with 17 goals and 169 goals to achieve the three dimensions of development. sustainable: social, economic and environmental in an integrated and balanced way. With this, the objective of this review is in line with the objectives addressed in items 2 ("End hunger, achieve food security and improved nutrition and promote sustainable agriculture"), 12 ("Ensure sustainable consumption and production patterns") and 15 ("Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss"), where there is the identification of

biologically-based functional ingredients that can promote food safety and nutrition for humans; identifies a possible route for the efficient use of natural resources, encouraging the reduction of food waste along the production chains; as well as the promotion of protective measures, restoration and sustainable use of terrestrial ecosystems.

2. Reuse of fruits and vegetables biowaste: environmental and economic perspective

In fruit and vegetable waste, there are mostly inedible parts (stalks, seeds and peels) and also edible parts that are rotten, damaged and with low quality, that may be representative of raw materials rich in compounds of great interest, such as bioactive compounds and biopolymers. As a renewable raw material, available in abundance and at low cost, fruit and vegetable biowastes can be used to obtain new ingredients with functional characteristics, natural ingredients with preservative function, nutraceuticals and/or pharmaceuticals, biofuels, biofertilizers, enzymes that add economic value and reduce environmental impact (Kumar et al., 2017; Magama et al., 2022).

The problematization that involves the management of fruit and vegetable waste treatment is due to its characteristics of high biodegradability, moisture content and organic load in which the procedures normally performed are inefficient for an adequate purpose. In order for this problem to have plausible solutions, several researches were carried out in order to find management alternatives in the treatment of fruit and vegetable waste that are more efficient, environmentally correct and at an affordable cost (Magama et al., 2022). In this way, different processes and business models can be developed with the objective of promoting a valorization of fruit and vegetable biowaste in a concept called "industrial symbiosis", where the by-products of one industry can be used as raw material in another sector, completing the production cycle and cultivating the circular economy (Simões et al., 2021).

The circular economy is a widely used conceptual model for the correct management of agro-industrial waste to perform sustainable development based on the bioeconomy. Its implementation by the industries that generate fruit and vegetable waste can bring economic and environmental benefits; however, the problems involving geographical aspects must be very well addressed, since all logistics must be accounted for so that it does not have a direct impact on the sustainable use of these surplus products (Ubando et al., 2020).

The use of biorefineries can enhance the value of the different components present in the composition of fruits and vegetables, where their facilities promote an integrated, efficient and flexible conversion through physical, chemical, biochemical and thermochemical processes into products with added value (Simões et al., 2021). The valorization of fruit and vegetable biowastes can be carried out by several industrial sectors, and applied as a substrate for solid-state fermentation, enzyme and biofuel production, biofertilizer production, chemical compounds, films, among others (Yaashikaa et al., 2022). Table 1 exposes some studies performed for this purpose.

The fruit and vegetable biowaste can also be used in the food and pharmaceutical sectors, through the production of natural ingredients and nutraceuticals with interesting functional characteristics (Yaashikaa et al., 2022). However, one of the limitations of reusing these wastes is the lack of biomass standardization, considering that its physical-chemical, sensory and bioactive characteristics can be influenced by the cultivation method used, as well as climate, location, type and origin of this biowaste (Brito et al., 2020). Therefore, in order to overcome this limitation and find the best destination for biowaste, advances in scientific studies are needed and identifying potential valorization routes that provide greater economic value rather than being discarded in the environment.

Table 1

Different products obtained from fruits and vegetables.

Obtained product/compound	Process	Vegetables waste	Reference
Fermentable sugars	Acid and enzymatic hydrolysis	Potatoes	Bansal et al. (2022)
		Apple	Luo and Xu (2020)
	Reactive extrusion technology	Olive	Doménech et al. (2020)
	Ultrasound assisted extraction	Courgette	Kopczyńska et al. (2021)
	Enzyme assisted extraction	Okra	Olawuyi et al. (2020)
Ethanol	Enzyme and microwave co-assisted extraction	Radish	Lin et al. (2022)
	Acid assisted extraction and enzymatic hydrolysis	Chicory	Stökle et al. (2020)
	Bacterial fermentation	Banana	Sarkar et al. (2020)
	Organosolv pretreatment, enzymatic hydrolysis and fermentation	Potato	Soltaninejad et al. (2022)
Biogas	Acid and enzymatic hydrolysis and fermentation	Potato	Omar et al. (2020)
	Anaerobic digestion	Banana	Achinas et al. (2019)
		Cucumber	Lowe et al. (2020)
	Anaerobic co-digestion	Cabbage & Cauliflower	Beniche et al. (2021)
Food-grade sulforaphane	Ethanol extraction	Broccoli	González et al. (2021)
		Carrot	Salvañal et al. (2021)
Lactic acid	Soxhlet extraction and submerged fermentation	Yam	Ajala et al. (2021)
	Acid hydrolysis and submerged fermentation	Olive	Kostas et al. (2020)
Bio-oil	Microwave pyrolysis	Pumpkin	Reddy et al. (2021)
		Peanut	Ma et al. (2020)
Bio-based carbon materials	Hydrothermal treatment	Potato	Hoffmann et al. (2020)
		Hydrothermal carbonization and pyrolysis	Apple
Bio-based films and 3D objects	Casting and compression molding	Banana	Li et al. (2019)
Bio-based epoxy resin	Liquefaction with sulfuric acid		

3. Fruits and vegetables biowaste as a source of interesting compounds

Fruit and vegetable biowaste comprise peels, stalks, pulp and seeds and also whole products, which are discarded because they do not have the marketing characteristics that meet consumer expectations (Taghian Dinani & van der Goot, 2022).

These raw materials have a highly complex chemical structure, with a matrix rich in bioactive compounds, such as phenolic compounds, carotenoids, tocopherols, vitamins and complex carbohydrates such as cellulose, hemicellulose, fibers, proteins, fats, organic acids and minerals (Simões et al., 2021). They also have a high water content and organic load, making them susceptible to rapid contamination and bacterial degradation, leading to the need for their correct management (Kosseva, 2020).

As they present a wide range of valuable compounds in their composition, fruit and vegetable biowastes have been the subject of

several studies, by the scientific community, in order to obtain ingredients rich in interesting compounds, that can be incorporated for different purposes. Table 2 shows some of these examples.

According to data available in the literature, there are two forms of incorporation and development of new functionalized products: through flour and extracts. In a work carried out by Segura-Badilla et al. (2022), banana peels were used under microbiologically safe conditions to obtain a fine flour, and its incorporation of 5–20% in baked goods and pastas was evaluated as a substitute for wheat flour. From the results, it was possible to observe that an incorporation of 5%–10% of banana peel flour can provide extra nutritional value without affecting the sensory characteristics of the products. Through the chemical composition analysis of the banana peel, an interesting content of crude fiber (14.38%), protein (6.41%) and carbohydrates (57.13%) were observed.

Also, Jose et al. (2022) evaluated the use of pineapple biowaste to obtain flour and its incorporation into cookies at different concentrations (5%, 10%, and 15%). The incorporation of this biowaste promoted an increase in dietary fiber content and carbohydrate content and a decrease in protein and fat content, a low gluten content, and an increase in antioxidant activity, with the incorporation of 15% of the flour in the cookies. Kaur et al. (2022) used potato peel flour to replace wheat flour at levels of 1–7% in biscuit formulations. Considering the results, the authors observed that a substitution of 1–2% promoted an increase in the nutritional value of the biscuits, as well as an increase in phenolic content, fiber and antioxidant capacity, without interfering with the color, appearance, taste and texture attributes of the biscuits.

Analyzing individually, dietary fibers present in biowastes can be extracted and included in food products as non-caloric and low-cost bulking agents, water and oil retention enhancers and to improve emulsion or oxidative stability (Pathania & Kaur, 2022). The inclusion of dietary fibers in human food helps in the prevention of cardiovascular diseases and obesity and also in the improvement of intestinal health (Santos et al., 2022).

In a study carried out by Li, Akram, et al. (2020) the date pits were used to extract dietary fibers and other compounds such as phenolic acids, flavonoids and other antioxidants from the subcritical water extraction technique. The results showed that it was possible to obtain a yield of 29 g/mg of dietary fibers, in addition to 997 mg gallic acid

equivalent/100 g, 352 mg quercetin equivalent/100g and 167 mg trolox equivalent/100g. Soluble and insoluble dietary fibers were extracted from the fruits of *Rubus chingii* Hu. by four different extraction methods by the authors Wang, Fang, et al. (2022), in order to obtain an ingredient with potential for application in functional foods or as a natural additive. The results showed that the water and acid extraction methods were more efficient in obtaining fibers, reaching a content of 19.89 g/g and 12.62 g/g, and an efficacy in soybean oil absorption. Additionally, through experiments with animals, a decrease in triglyceride levels and the promotion of fat excretion, which are harmful symptoms for cardiovascular health, were observed, suggesting that these two methods are effective in obtaining dietary fibers from *Rubus chingii* fruits.

Complex carbohydrates present in the composition of the cell wall of plants are also components of great interest in the recovery of fruit and vegetable biowastes, and can be converted into bioenergy such as ethanol (Chatterjee & Mohan, 2021; Sarkar et al., 2020) and biohydrogen (Cieciora-Wloch et al., 2020), in addition to compounds such succinic acid (J. Wang, Fang, et al., 2022), acetic acid (Vashisht et al., 2019) and lactic acid (Fazzino et al., 2021; Ngouénam et al., 2021). For this, sugar depolymerization strategies are necessary through mechanical, thermal or chemical methods where complex sugars are converted into reducing sugars that can be easily fermented (Chatterjee & Mohan, 2021).

Another component of interest is pectin, a polysaccharide present in the cell wall, which can be extracted by physicochemical processes and used in the food industry as an excellent functional ingredient for promoting benefits in the prevention of diabetes and in the reduction of blood cholesterol, in addition to have low calorie and fat content; in the cosmetics industry it is used as a stabilizer in hair preparations and in the prevention of skin aging (Sabater et al., 2022).

In the group of bioactive compounds, the carotenoids are soluble compounds in fat and have a characteristic yellow to yellow-orange colour, evidencing an important antioxidant potential. This happens because there are components in its chemical structure that are capable of fixing monomolecular oxygen during phytochemical processes. Carotenoids can be divided into carotenes: β -carotene and lycopene, and xanthophylls (astaxanthin, β -cryptoxanthin, canthaxanthin, capsanthin-capsorubin, fucoxanthin, lutein and zeaxanthin) (Rowles & Erdman,

Table 2

Compounds of interest obtained from different fruits and vegetables, using distinct extraction techniques.

Product/ compound	Vegetables waste	Process	Yields	References
Phenolic compounds	Grape	UAE	24.63 mg GAE/g of TPC	Romanini et al. (2021)
	Plum		211.15 mg GAE/100 g of TPC	Savic and Savic Gajic (2021)
	Garlic		5.84 mg GAE/g of TPC	Cavalcanti et al. (2021)
	Papaya	SWE	91.06 \pm 3.00 mg GAE/g of TPC	Rodrigues et al. (2019)
	Radish	EAE	45.9 mg GAE/g of TPC	Rani et al. (2021)
	Okra	MAE	68.02 mg GAE/g of TPC	Amirabbasi et al. (2021)
			UAE	50.67 mg GAE/g of TPC
		HAE	39.11 mg GAE/g of TPC	
Colorants	Cashew apple	MAE	41.01 mg GAE/g of TPC	Patra et al. (2021)
	Beetroot	PEF	\sim 7.00 mg/100 g of betanin	Nowacka et al. (2019)
	Beetroot	CE	1.20 mg/g of betain	Lazár et al. (2021)
	Jabuticaba	HAE	81 mg/g TAC	Albuquerque et al. (2020)
Carotenoids	Jambolan	PLE	47.05 mg/g TAC	Sabino et al. (2021)
	Red bell pepper	PEF and UAE	812 mg/100 g of TCC	Rybak et al. (2020)
	Mango	SFE	1.9 mg all- <i>trans</i> - β -carotene equivalent/g	Sánchez-Camargo et al. (2019)
Protein	Orange	CE using DES	653.51 mg de β -caroteno/100 g	Viñas-Ospino et al. (2023)
	Pea	Alkaline extraction	73.6%	Petersen et al. (2020)
	Pumpkin		23%	Vinayashree and Vasu (2021)
Pectin	Pumpkin		70.31%	Lalnunthari et al. (2020)
		Ethanol acid extraction	69.89%	
	Carrots	Hydrothermal extraction	29.3 g/Kg	Ramos-Andrés et al. (2021)
	Orange	Acid hydrolysis	628.018 kg/m ³	da Costa et al. (2022)

UAE: Ultrasound assisted extraction; SWE: Subcritical water extraction; EAE: Enzyme assisted extraction; MAE: Microwave assisted extraction; HAE: Heat assisted extraction; PEF: Pulsed electric field; CE: Conventional extraction; PLE: Pressurized liquid extraction; SFE: Supercritical fluid extraction; DES: Deep eutectic solvents; TPC: Total phenolic compounds; TAC: Total anthocyanin content; TCC: Total carotenoid content; GAE: Gallic acid equivalent.

2020). Several studies have reported that these compounds have several benefits to human health, acting in the prevention of diseases such as cancer (Rowles & Erdman, 2020), diabetes mellitus, obesity, hypertension (Keller et al., 2021), cardiovascular diseases (Raju et al., 2021), among others. Due to its high antioxidant activity, carotenoids have the ability to interrupt the formation of free radicals and, as a consequence, reduce oxidative stress. Therefore, they can also contribute to the intervention of the aging process (Majumder & Annegowda, 2021).

Due to their coloring, natural carotenoids have great interest to the industry to be used as colorants in foods, beverages, confectionery, supplements and medicines (Rowles & Erdman, 2020). They can be found in carrots, oranges, avocados, melons, sweet potatoes, spinach, tomatoes, broccoli, among others (Pradhan et al., 2022). The authors Ordóñez-Santos et al. (2021) carried out in their study an optimization of the ultrasound assisted extraction process of tangerine epicarp samples, in which they obtained an optimized extract with total carotenoid yield of 140.70 ± 2.66 mg β -carotene/100 g dry sample. Subsequently, they added the extract in bakery products and verified that the carotenoid extract, a natural component, can be an alternative to synthetic coloring such as tartrazine used as a component in this sector.

Also, tocopherols are fat-soluble compounds present in a wide range of foods. The vitamin E is a biologically active form that behaves as a fat-soluble antioxidant and acts in the prevention of free radical chain reactions and reducing the risk of several chronic diseases, such as cancer, diabetes, aging and cardiovascular disease (Bora et al., 2022). This vitamin has a group of eight essential compounds, four are tocopherols (α , β , γ and δ) and four tocotrienols (α , β , γ and δ), with α -tocopherol being the compound with the highest biological activity that is present in greater amounts in vegetable oils, such as almond, olive, sunflower, among others (Jain et al., 2022).

With the discoveries related to the benefits that vitamin E promotes to the human body, research involving the use of this vitamin in several industrial areas such as food, cosmetics and pharmaceuticals has been stimulated. In the food industry, vitamin E has great application as a food additive capable of preventing food oxidation, improving its quality and increasing its shelf life (Shahidi et al., 2021). The authors Keshari et al. (2022) evaluated the supplementation of α -tocopherol acetate in alginate-based coatings to increase the shelf life of fresh-cut carrots. They found that it is an effective preservative as it reduces weight loss and microbial counts, promotes an effect positive in conserving the concentration of total phenolic compounds, reducing sugars and antioxidant activity.

Finally, within the bioactive compounds available in fruits and vegetables phenolic compounds stand out as the most studied due to their various benefits associated with human health (Routray et al., 2022). They are mainly arranged in the bark of biowastes, which, through sun exposure, promote a greater synthesis of flavonoids that protect plant parts against various harmful external factors (Osojnik Črnivec et al., 2021).

4. The particular case of phenolic compounds

4.1. Biochemical characterization of phenolic compounds

Phenolic compounds are a representative group of phytochemicals produced by most plants as an integral part of their structure. To date, more than 8.000 structural variants have been identified in several vegetable species (Alara et al., 2021).

One of the characteristics of these molecules is the presence of at least one aromatic ring linked to one or more hydroxyl groups, a structure that can range from a simple phenolic molecule to complex polymers with high molecular weights (Vuolo et al., 2019).

Phenolic compounds play an important role in plant metabolism, namely are responsible for the defense of plants against ultraviolet radiation, cold and dry temperatures, or against herbivores, parasites and pathogens, in addition to conferring organoleptic characteristics to fruits

and vegetables (Tresserra-Rimbau et al., 2018). Due to the protective role played in the plant organism, these compounds have also a great antioxidant and antimicrobial capacity, which has been gaining prominence in different areas of research, including food, pharmaceutical and cosmetic industries (Wong-Paz et al., 2017).

The scientific community has been studying these compounds, founded in fruits and vegetables, for their benefits in improving human health in different industrial applications, so they are proposed as one of the main bioactive compounds of these biomasses (Agcam et al., 2021; Gómez-Cruz et al., 2020; Martínez-Fernández et al., 2021; Patra et al., 2021; Rocha & Noreña, 2020; Rodrigues et al., 2019; Savic & Savic Gajic, 2021; Villacís-Chiriboga et al., 2021; Yasaminshirazi et al., 2020). Fig. 1 shows a scheme with the identified classes of phenolic compounds present in fruits and vegetables, in which they can be extracted and applied in different industrial sectors due to their bioactive characteristics of great interest.

There are a large number of known structures of phenolic compounds characterized according to the number of aromatic rings present in their structure (Bondam et al., 2022). Considering this, at least five highlighted as being of major importance in the human diet: the phenolic acids, the flavonoids, the tannins, the stilbenes and the lignans (Albuquerque et al., 2021; Vuolo et al., 2019).

Phenolic acids are formed by an aromatic ring called benzene, in which the hydrogen atoms are replaced by carboxylic acids and/or hydroxyl groups (Arias et al., 2022). Hydroxycinnamic acids, a class of phenolic acids, are derived from cinnamic acid and found as simple

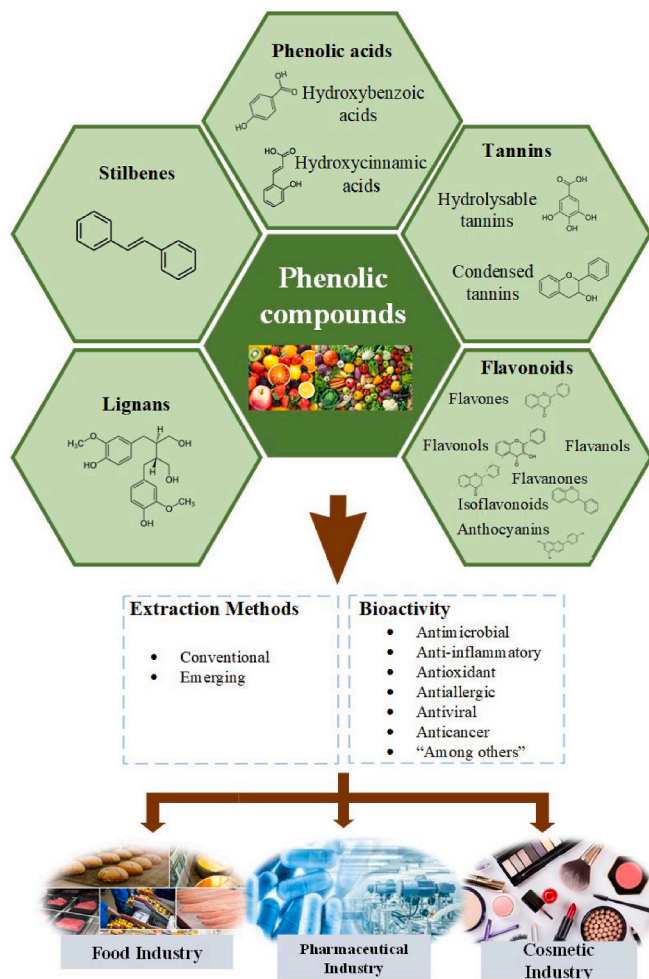


Fig. 1. Scheme of the classification of phenolic compounds and their application possibilities (adapted from Albuquerque et al. (2020)).

esters with quinic acid or glucose. The most common forms of hydroxycinnamic acids are ferulic, caffeic, *p*-coumaric and sinapic acids. Another class is the hydroxybenzoic acids derived from benzoic acid and found in the soluble form associated with sugars or organic acids and/or linked with lignin. *P*-hydroxybenzoic, gallic, protocatechuic, vanillic and syringic acids are the most common forms of hydroxybenzoic acids (Kumar & Goel, 2019). One of the main advantages of phenolic acids lies in their availability, most often in the free form, which favors their bioavailability, solubility and, consequently, their absorption in the gastrointestinal tract (Arias et al., 2022).

Flavonoids are compounds that have numerous health benefits, being known for their antioxidant, anti-inflammatory, antiallergic, antiviral activities, and as anticancer agents by reducing the enzymes that cause tumors, making them indispensable compounds in pharmaceutical, medicinal and cosmetic applications. They are found in fruits and vegetables as glycosylated or esterified forms composed of two aromatic carbon rings: benzopyran and a benzene ring (Gupta et al., 2022). The group of flavonoids includes flavones such as apigenin and luteolin, flavonols such as kaempferol and quercetin, isoflavones such as daidzein and genistein, flavanones such as hesperetin and engeletin, flavanols such as epigallocatechin, epicatechin and catechin, anthocyanins such as pelargonidin, cyanidin and malvidin (Singh & Hembrom, 2019). Flavones and catechins are considered the most potent flavonoids in terms of providing protection to the human body (Gupta et al., 2022). An important consideration to have with flavonoids is the question of their bioavailability, which is limited and must be evaluated in order to provide full health benefits to the human body (Arias et al., 2022).

Another class of phenolic compounds with great importance are tannins which are found as phenolic polymers in fruits. The tannins can be of the condensed and hydrolysable type that present astringent and bitter characteristics with different molecular weights, being only the hydrolysable tannins capable of solubilizing in water. They also have the ability to precipitate proteins (Vuolo et al., 2019). The class of stilbenes and lignans are less pronounced in studies that report on phenolic compounds, but they have their advantages, especially resveratrol in the class of stilbenes; it is present in grapes and peanuts as a compound widely known for its bioactivities as well as antioxidant, anti-inflammatory and cardioprotective activities (Albuquerque et al., 2021).

4.2. Bioactive action of phenolic compounds

The bioactive action of phenolic compounds is a subject of great interest that has attracted many researchers over the years. The antioxidant, antimicrobial, antiallergic, anti-inflammatory, anticancer, cardioprotective potential, among others, is highlighted when the bioactive potential is investigated (Villegas-Aguilar et al., 2022).

The main mechanism of bioactive action of phenolic compounds is related to their antioxidant potential, in which they have high efficiency and potential to reduce hydroxyl, superoxide and peroxy free radicals, in addition to acting against other non-radical compounds that are also associated with oxidative stress and cellular damage, such as hydrogen peroxide and hypochlorous acid (Arias et al., 2022). In addition to preventing the formation of free radicals, they can also act to eliminate already formed radicals, oxygen singlets and photosensitizing compounds, as well as inhibit or stimulate enzymes related to oxidative stress, which is the main cause of diseases and imbalances in humans, animals and plants (Olszowy, 2019; Villegas-Aguilar et al., 2022).

The benefits associated with these compounds can be affected by some factors and bioavailability is the main one due to their presence in foods as glycosides, which limits their absorption in their natural form (Tresserra-Rimbau et al., 2018). Many works only prove its bioactive action *in vitro*, making it necessary to gather more information on its *in vivo* action, since several conditions can interfere with the absorption of these compounds by the human body (Albuquerque et al., 2021).

In a study performed by Bedrníček et al. (2020) the effect of adding

onion biowaste fractions to gluten-free bread to promote health benefits was investigated. Fried, dried and peeled onions were used, the latter promoting greater antioxidant activity, phenolic and flavonoid content in the breads. The authors reported that the glycosides, dimers and trimers of quercetin in breads enriched with onion skins were decomposed during cooking and released quercetin in its free form, indicating thermal stability of this compound. Bread enriched with onion husks significantly increased antioxidant activity in the blood of consumers evaluated compared with control bread. The results presented suggest that the onion skin incorporated in gluten-free breads leads to an increase in the biological value with a satisfactory acceptance by consumers.

Mori et al. (2019) conducted a study evaluating the effect of supplementation with some phenolic compounds (–)–epigallocatechin-3-gallate and ferulic acid, on the improvement of cognitive capacity in mice with a pathology similar to Alzheimer's disease. In this study, a three-month combined treatment with orally administered phenolics at a dose of 30 mg/kg each, resulted in improvements in learning and memory tests in mice, reversing cognitive impairment, as well as additional beneficial effects on the improvement of neuroinflammation, oxidative stress, and synaptotoxicity.

4.3. Phenolic compounds as a natural ingredients with preservative, functional and colorant action

In addition to all the benefits associated with phenolic compounds regarding the improvement of human health, there is the antimicrobial and antioxidant capacity in which molecules that can be used as preservatives in foods, promoting an increase in the shelf life of the product (Albuquerque et al., 2021). As they are obtained from natural sources (fruits and vegetables) they are generally considered safe for human consumption. So, there is a great preference by consumers when compared to synthetic ingredients. Fruits and vegetables such as broccoli, Chinese chives, leek, cherry, curry, garlic, ginger, grape, green tea, mint, lemon grass, onion, pomegranate, potato, pumpkin and among others are used as a natural vegetable source to obtain extracts with preservative capacity (Shah & Mir, 2022).

The antioxidant action mechanism of phenolic compounds occurs by inhibiting or interrupting the formation of free radicals that are precursors of the oxidation reaction, by donating a hydrogen atom to the radical. The mechanism of antimicrobial action is not well defined, since plants have a great diversity of compounds with different molecules, and therefore, there may be different mechanisms of antimicrobial action such as coagulation of cytoplasmic, membrane protein damage, cell wall destruction, reduction of proton motive force, damage cytoplasmic membrane, increased permeability and consequent leakage of cell contents and others (Beya et al., 2021). Phenolic compounds can also inhibit ATP and DNA synthesis (Efenberger-Szmechtyk et al., 2021).

Catechin and gallic, vanillic, ferulic and protocatechuic acids of the flavonoid and phenolic acid class, respectively, from mango biowaste extracts were evaluated for the growth control of two probiotics and two pathogenic bacteria in a study carried out by Pacheco-Ordaz et al. (2018). The results showed that the presence of catechin combined with protocatechuic or vanillic acid allows the growth of probiotics and inhibits the proliferation of pathogenic bacteria, acting selectively without affecting the viability of the probiotics.

In a study carried out by the Martiny et al. (2021) researchers, where they evaluated the antimicrobial action of olive leaf extract, they verified action against the bacteria *Escherichia coli* with a minimum inhibitory concentration (MIC) of 50 mg/mL. In the study carried out with canned radishes, by the researchers Li, Akram, et al. (2020), the compounds 2,6-dihydroxyacetophenone (DHAP) showed a good antimicrobial action against *E. coli*, *Bacillus subtilis* and *Candida albicans* and the compound 4-hydroxybenzaldehyde (HBA) only against *E. coli* and *C. albicans*.

In a study carried out by Añibarro-Ortega et al. (2020), the extract

obtained from tomato biowastes was evaluated for its antimicrobial capacity. The results showed higher antibacterial capacity against *Salmonella typhimurium*. However, the extract did not prove good antifungal activity. The authors identified quercetin-3-O-rutinoside as the main phenolic compound in the extract.

Also, [Silva et al. \(2021\)](#) evaluated the extract of eggplant, from the whole fruit, epicarp and pulp, rich in anthocyanins, regarding its antioxidant and antimicrobial capacity. The results for antioxidant activity (IC50) ranged from 135 to 8941 µg/mL, with the extract from the epicarp showing the highest activity. Regarding antimicrobial capacity, all extracts showed bactericidal and fungicidal activity for all strains tested, with *Escherichia coli* being the most susceptible.

The authors [Mattje et al. \(2019\)](#) incorporated ginger oil, obtained by supercritical CO₂ extraction, into tilapia burger formulations and its quality change was observed during 8 days under refrigerated storage. The formulation enriched with ginger oil showed good antioxidant activity and increased the shelf life of the products from 6 to 8 days, being similar to that observed by the formulation with the synthetic antioxidant, suggesting that ginger oil was a good alternative to replace commercial antioxidants in meat and fish products.

Chamomile and fennel extract were incorporated into yogurt samples by the authors [Caleja et al. \(2016\)](#), as a natural additive to increase the antioxidant activity of the product. The chamomile extract showed the highest antioxidant activity with the lowest EC₅₀ (EC₅₀ = 45 ± 3 mg/mL), followed by the fennel extract (EC₅₀ = 94 ± 4 mg/mL), being higher than that presented by the synthetic additive, potassium sorbate (E202) (EC₅₀ = 111 ± 20 mg/mL). Also [Caleja et al. \(2015\)](#) studied the action of fennel extract on cottage cheese samples with the aim of increasing the shelf life and antioxidant activity of the products. Fennel extract improved antioxidant properties until 14 days of storage (EC₅₀ = 49.44 ± 0.76 mg/mL), did not change the nutritional properties of the cheese and prevented yellowing until 7 days of storage. The cheeses used as control showed signs of degradation after 14 days of storage.

In addition to the preserving and functional capacity demonstrated by phenolic compounds, these also exhibit coloring properties ([Albuquerque et al., 2021](#)). Regarding the evaluation of the stability of these colorants compounds, [Araújo \(2019\)](#) conducted a study in which the stability of the anthocyanin-rich extract obtained from samples of red cabbage was evaluated. The study assessed the influence of anthocyanin co-pigmentation, lyophilized colorant formulation, and its stability over 15 days at temperatures of 10 and 25 °C. The use of gallic acid (1%) and tannic acid (1%) in the extract formulation resulted in good stability of the anthocyanins and color intensity after storage. Lyophilized colorants with acid, at different temperatures, had a degradation of 1%, while pure formulations resulted in degradation of 7.78% (25 °C) and 7.39% (10 °C). [Sampaio et al. \(2021\)](#) evaluated the stability of two anthocyanin-rich extracts obtained from varieties of colored potatoes incorporated into a soda formulation. The stability of the color was evaluated for 30 days, and the results were compared to a commercial colorant E163. All samples maintained color stability between day 0 and day 7 for all analyzed parameters. Only on day 30 did all formulations show a significant reduction in the intensity of the red color. Thus, the authors concluded that these extracts can be used as natural coloring ingredients with a coloring capacity similar to the control, as well as possessing interesting antioxidant and antimicrobial properties.

In the study conducted by [Backes et al. \(2020\)](#), the incorporation of anthocyanin extracts from fig and cherry tree peels was evaluated for use as colorant in pastry products (namely in donuts and a typical Brazilian sweet called "beijinho"). The results showed that the cherry tree extract slightly lost its color intensity after 24 h, but the fig peel extract maintained its coloration. Furthermore, the extracts improved the products in terms of lower consistency and firmness. Additionally, the extracts were tested for their antibacterial activity, and the fig extract showed slightly better results, with inhibition of one Gram-negative and two Gram-positive

bacteria. The authors mentioned that, due to these antibacterial characteristics, further studies should be conducted regarding the shelf-life extension, but that these extracts have great potential as natural colorants in pastry preparations, as well as acting as preservative compounds.

So, it is a fact that phenolic compounds have several beneficial effects on human health and preservative capacity to increase the shelf life of food preparations. However, it is important that scientific studies continue to be carried out and in an increasingly in-depth way, because there are several challenges in the final idealization of these natural ingredients at an industrial level that must be surpassed. Among the main challenges for obtaining products with natural ingredients are environmental stresses, processing and storage, interaction with macromolecules and the sensory changes they can promote to food ([Darvish et al., 2021](#)).

5. Conclusions and future perspectives

The growing of population has increased the need for better utilization of food and the development of sustainable strategies to promote safe and healthy products. The fruits and vegetables sector produces a large amount of biowaste throughout the entire supply chain, from production to consumption. However, it is possible to reuse this biowaste to extract phenolic compounds that are of great interest in the food and pharmaceutical industries.

The phenolic compounds found in biowaste have coloring, preservative and functional properties that can be used as natural ingredients in the food and pharmaceutical industries, to preserve food and promote human health benefits. The problem with obtaining these natural ingredients is in their extraction and stabilization in the phase of industrial processes, as well as in ensuring their bioavailability in adverse processing conditions and human digestive systems. Therefore, it is necessary to verify their action on health and food preservation, as well as studies on bioavailability and bioaccessibility, where the scientific community in partnership with the industrial sector advances in tests and methodological improvements, so that this reality becomes possible in the near future. The benefits of phenolic compounds are numerous and, therefore, research must advance in order to more practical information can be proven and improved to encourage industries to include this new range of ingredients in their production processes. All of this is so that new products with functional and nutraceutical characteristics can gain space in the market.

Authors contributions

Tatiane Oliveira: Conceptualization, Writing- Original draft preparation, Cristina Caleja: Writing- Original draft preparation, M. Beatriz P.P. Oliveira: Conceptualization, Writing- Reviewing and Supervision, Eliana Pereira: Conceptualization, Writing- Reviewing and Supervision, Lillian Barros: Conceptualization, Writing- Reviewing and Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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