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Bioactive compounds from by-products of eggplant: Functional properties, potential applications and advances in valorization methods

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ABSTRACT

Background: Eggplant (also known as aubergine) by-products, which consist mostly of peel and calyx, are generated in substantial amounts by industrial food processing sections and usually discarded as waste without further utilization. However, studies have demonstrated that these by-products are superb sources of bioactive compounds. Therefore, the disposal of eggplant by-products not only gives rise to environmental and economic consequences but also represents a tremendous loss of valuable materials.

Scope and approach: This review is aimed to assess the potentials of eggplant by-products as a source of bioactive compounds by evaluating the functional properties and production approaches of the bioactives and exploring their applications in food and pharmaceutical industries.

Key findings and conclusions: It is estimated that over ten million tonnes of eggplant by-products are generated annually. The peel is an outstanding source of delphinidin-derived anthocyanins with remarkable antioxidant, antimicrobial and anticancer properties. Moreover, both peel and calyx are high-yielding sources of pectin with excellent functional properties. Several methods, from conventional approaches to ultrasound and microwave-assisted techniques, have been developed and optimized for extraction of anthocyanins and pectin. Furthermore, integrated valorization of eggplant by-products, which consists of simultaneous extraction of phenolics and pectin followed by production of pullulan from the leftovers, has shown promising results. It is also demonstrated that eggplant peel anthocyanins are potent alternatives to synthetic additives for fortification and shelf-life improvement of food products. However, further studies are required in regards to the integrated valorization technique, health-promoting properties and food and pharmaceutical applications of these bioactive compounds.

1. Introduction

Every day, a massive amount of agricultural by-products is generated as a result of fruit and vegetable production and storage, industrial utilization and commercial and household consumption around the world. Industrial food processing plants are responsible for a considerable bulk of these by-products, which consist mostly of unutilized plant tissues such as peels, husks, calyxes and seeds (Jimenez-Lopez et al., 2020). These by-products remain mostly without further utilization. Thus, they are usually discarded as waste in landfill sites, giving rise to serious environmental complications and economic expenses (Mauro et al., 2020). Furthermore, over the past decades due to a steep rise in both the human population and production of crops, the aforementioned issues have only been exacerbated over time. However, most of these by-products could be valorized using various technological and biotechnological practices and have the potential to yield high levels of

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Abbreviations: EB, Eggplant by-products; EP, Eggplant peel; EC, Eggplant calyx; EBP, Eggplant by-product pectin; EPP, Eggplant peel pectin; ECP, Eggplant calyx pectin; EPE, Eggplant peel extract; TPC, Total phenolic content; WHC, water holding capacity; OHC, Oil holding capacity; DE, degree of esterification; GalA, Galacturonic acid; RG-I, Rhamnogalacturonan I; RG-II, Rhamnogalacturonan II; HMP, High methoxyl pectin; LMP, Low methoxyl pectin; SLE, Solid-lipid extraction; SFE, Supercritical fluid extraction; UAE, Ultrasound-assisted extraction; MAE, Microwave-assisted extraction; GAE, Gallic acid equivalent.

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valuable bioactive compounds (Coelho et al., 2020).

Valorization of fruit and vegetable by-products is an efficient and strategic approach to pull the waste out of the environment, acquire value-added compounds from them and put those compounds back into the economy; thereby, addressing both related environmental and economic concerns. For example, other than reducing the depletion rate of natural resources, waste accumulation and landfilling costs, valorization of these by-products could promote innovation, provide business opportunities and ultimately, generate revenue from a formerly costly waste material (Talekar et al., 2018). Furthermore, consumer demand for food, pharmaceutical and cosmetic products that contain natural, health-promoting additives instead of synthetic substances, has been increasingly growing over the past years. Therefore, these concerns have attracted the interest of scientists and industries to try to develop diverse techniques for utilization of fruit and vegetable by-products as an inexpensive, abundant and high potential source of valuable bioactive compounds (Arjeh et al., 2020).

Eggplant (*Solanum melongena* L.) is a high yielding and affordable agricultural crop from the solanaceous family, which is cultivated in a wide variety of shapes, sizes and colors. Eggplant is native of India, while secondary origin sources are from China and Japan. Today, it is widely cultivated in other parts of Asia, as well as Europe, Africa and America (Niño-Medina et al., 2017). The interest for the cultivation of eggplant is rapidly growing around the world due to its high nutritional values and extensive applications in formulating various types of fresh, frozen, and canned foods, such as pickled, fried, grilled, or stuffed eggplant, as well as several cuisines like eggplant kibbeh, kashke bademjan and different eggplant stews (Gürbüz et al., 2018; Horincar, Enachi, Barbu, et al., 2020). However, industries that are manufacturing such products are also responsible for generating considerable amounts of eggplant by-products (EB), most of which are treated as waste and discarded in landfills. Peel and calyx are the main by-products of eggplant. The peel is an incredibly rich source of anthocyanins (Mauro et al., 2020). Moreover, both peel and calyx are great sources of dietary fibers, such as pectin and cellulose (Kazemi et al., 2019a; 2019b). Therefore, regardless of discussed environmental and economic issues, disposal of EB as waste represents a massive loss of valuable materials.

In this review, the available information and literature in regards to EB and their potential as a valuable source of bioactive compounds are gathered and summarized. For this purpose, the annual production, main bioactive compounds and valorization methods of EB have been discussed and possible applications of the bioactive compounds in food and pharmaceutical industries have been reviewed.

2. Quantification of eggplant by-products

Worldwide eggplant cultivation data are presented in Table 1 (FAOSTAT, 2019). They show a global production of 55,197,878 tonnes, with Asia contributing to more than 94% of total production, followed by Africa (3.4%), and Europe (1.7%). As seen in Table 1, the total eggplant cultivation area for the top five countries (China, India, Egypt, Turkey, and Iran) is estimated at 1,597,200 ha with a total production of 50,908,619 tonnes (more than 92% of global production) and average production yield of ~31.87 tonnes per hectare.

The amount of generated by-products from an eggplant varies based on cultivar, size and ripening stage. However, based on an analysis performed by authors on 20 fresh, grade-A, dark eggplants (*Solanum melongena* L. var. *esculentum*) from the fields of Pishva city in Iran, it is estimated that an eggplant with an average fresh weight of 198.7 g provides 81 g of calyx and 284 g of peel (total percentage of by-products: 18.36%, calyx: 4.07% peel: 14.29%). Thus, it could be estimated that around 10,134,330 tonnes of EB is generated annually. However, not all of these by-products are available, for instance, the by-products generated by restaurants or household consumption are hardly accessible. Furthermore, the amount of eggplants that become damaged and spoiled on the field or during transportation and storage should be excluded from this estimation. Even so, a substantial percentage of these 10,134,330 tonnes of EB, which are inexpensive, available and outstanding sources of bioactive compounds, are still being generated by industrial food processing sections. These by-products contain high amounts of moisture (approximately 90%), along with organic components (Doulabi et al., 2020), meaning that they putrefy easily. Thus, if discarded inappropriately, EB could pose serious threats to the environment, such as greenhouse gas emission, unpleasant odor release and attraction of vermin (Mirmohamadsadeghi et al., 2019). Conclusively, valorization could be considered as the most efficient and harmless approach in regards to the handling of EB.

3. Bioactive compounds

3.1. Phenolic compounds

Phenolic compounds or phenolics are the most studied bioactive compounds that can be acquired from EB. These compounds are secondary metabolites, produced during plant growth and reproduction phases for various purposes, for example, as a response to environmental stress, defense against diseases and protection from UV radiation. Eggplant is known to have a considerably high antioxidant potential among various crops because of its significant amount of phenolic compounds. A good portion of these phenolics, approximately 30–60% (Mauro et al., 2020), is concentrated at the by-products of this crop, especially the peel. Therefore, EB are incredibly rich sources of phenolic compounds, comparing to other agricultural by-products (Gürbüz et al., 2018). The amount and composition of eggplant phenolics and the percentage of concentrated phenolics in EB could vary depending on the agronomic condition of the plant (such as plant species, cultivar, developmental stage, etc.) and environmental factors (such as climate and season factors, light and water availability, pH, etc.). For instance, Luthria et al. (2010) reported that the eggplant cultivar has a much more determinative role in the amount of phenolic compounds, comparing to

Table 1
Top 10 eggplant cultivation data (FAOSTAT, 2019) and possible by-product generation.

Country information			Statistics of eggplant			Possible EPP generation		Possible ECP generation	
Name	Rank (Production)	Rank (Yield)	Area (ha)	Production (t)	Yield (Hg/ha)	Wet basis (t)	Dry basis (t)	Wet basis (t)	Dry basis (t)
China (mainland)	#1	#2	781,695	35,555,562	454,852	5,080,890	462,222	1,447,111	142,222
India	#2	#8	727,000	12,680,000	174,415	1,811,972	164,840	516,076	50,720
Egypt	#3	#7	43,818	1,180,240	269,350	168,656	15,343	48,036	4721
Turkey	#4	#3	23,337	822,659	352,513	117,558	10,695	33,482	3291
Iran	#5	#6	21,350	670,158	313,891	95,766	8712	27,275	2681
Indonesia	#6	#9	43,954	575,392	130,908	82,224	7480	23,418	2302
Japan	#7	#4	8650	301,700	348,786	43,113	3922	12,279	1207
Italy	#8	#5	9550	300,620	314,785	42,959	3908	12,235	1202
Philippine	#9	#10	21,819	249,890	114,529	35,709	3249	10,171	1000
Spain	#10	#1	3470	238,325	706,484	34,057	3098	9700	953
World	–	–	1,847,787	55,197,878	298,724	7,887,777	717,572	2,246,554	220,792

environmental factors. In another study, Mauro et al. (2020) evaluated the effect of the ripening stage on peel anthocyanin and pulp caffeoylquinic acid contents of three different eggplant cultivars. They found out that the ripped *Black Bell* cultivar presented the highest amounts of peel anthocyanins and the lowest amount of pulp caffeoylquinic acids, while the ripped *Black Moon* cultivar was the exact opposite and the ripped *Birgah* cultivar demonstrated balanced percentages of both phenolic groups. They also suggested that in all three cultivars, eggplant over-ripening decreased the amount of anthocyanins while increased the amount of caffeoylquinic acids. Furthermore, the process conditions (such as storage, methods of extraction, etc.) could also significantly affect the amount of obtained phenolic from EB.

Niño-Medina et al. (2017) precisely reviewed the structure and content of various phenolic compounds of eggplant, of which flavonoids are mostly concentrated in the peel while phenolic acids are prominent in the plant's flesh. Anthocyanins, a subcategory of flavonoids, are the most dominant phenolics in EP, with reported contents varying from 8 to 85 mg per 100 g of peel (Dranca & Oroian, 2016). The structure of these bioactive compounds are constructed of two portions. The first one is called anthocyanidin, a molecule with a C_6–C_3–C_6 skeleton, which is two aromatic rings linked by an oxygenated heterocycle with three carbon atoms. The second portion is composed of one or several sugar molecules, which themselves, might be linked to acyl substituents (Belwal et al., 2020). These sugar molecules are linked to anthocyanidin aglycone through glycoside bonds, mostly, with C3–OH or C3–OH and C5–OH groups (Zhao et al., 2014). The difference between various types of anthocyanins is mainly dependent on the position, quantity and structure of these conjugate sugars, along with the number and position of hydroxyl and methoxyl groups in the anthocyanidin aglycone. More than 20 types of anthocyanidins are identified, However, the various types of plant anthocyanins are mostly derived from six of them: cyanidin, peonidin, pelargonidin, petunidin, malvidin and delphinidin (Tena et al., 2020).

EP anthocyanins are mostly derived from delphinidin aglycone. However, small amounts of cyanidin, peonidin and malvidin derivatives are also observed (Condurache et al., 2020; Ferarsa et al., 2018). Fig. 1A illustrates the structure of Delphinidin anthocyanidin. Delphinidin glycosides are also common in different berry cultivars and red wine. This non-methylated anthocyanidin, along with cyanidin and pelargonidin are the most abundant in nature, being found in 80% of pigmented leaves, 69% of fruits and 50% of flowers (Castañeda-Ovando et al., 2009). Among various delphinidin derivatives, which are responsible for the dark purple color of EP, the most significant ones are delphinidin-3-rutinoside (major anthocyanin in non-Japanese eggplant cultivars, especially eggplants in US market, Fig. 1B) and delphinidin-3-(*p*-coumaroylrutinoside)-5-glucoside, also known as nasunin (major anthocyanin in Japanese eggplant cultivars, Fig. 1C). Other delphinine-based anthocyanins such as delphinidin-3-rutinoside-5-glucoside, delphinidin-3-glucoside and delphinidin-3-rutinosyl-glucoside are also identified in EP with smaller contents (Gürbüz et al., 2018).

3.2. Pectin

Pectin, an essential component of the terrestrial plant cell wall, is a complex heteropolysaccharide with a broad range of applications and health-beneficial properties. This multifunctional compound has been the focus of various scientific studies and for the past several years, the demand for this compound has been annually increased by 4–5% in global markets (Kazemi et al., 2019a).

The structure of pectin is composed of three main blocks of

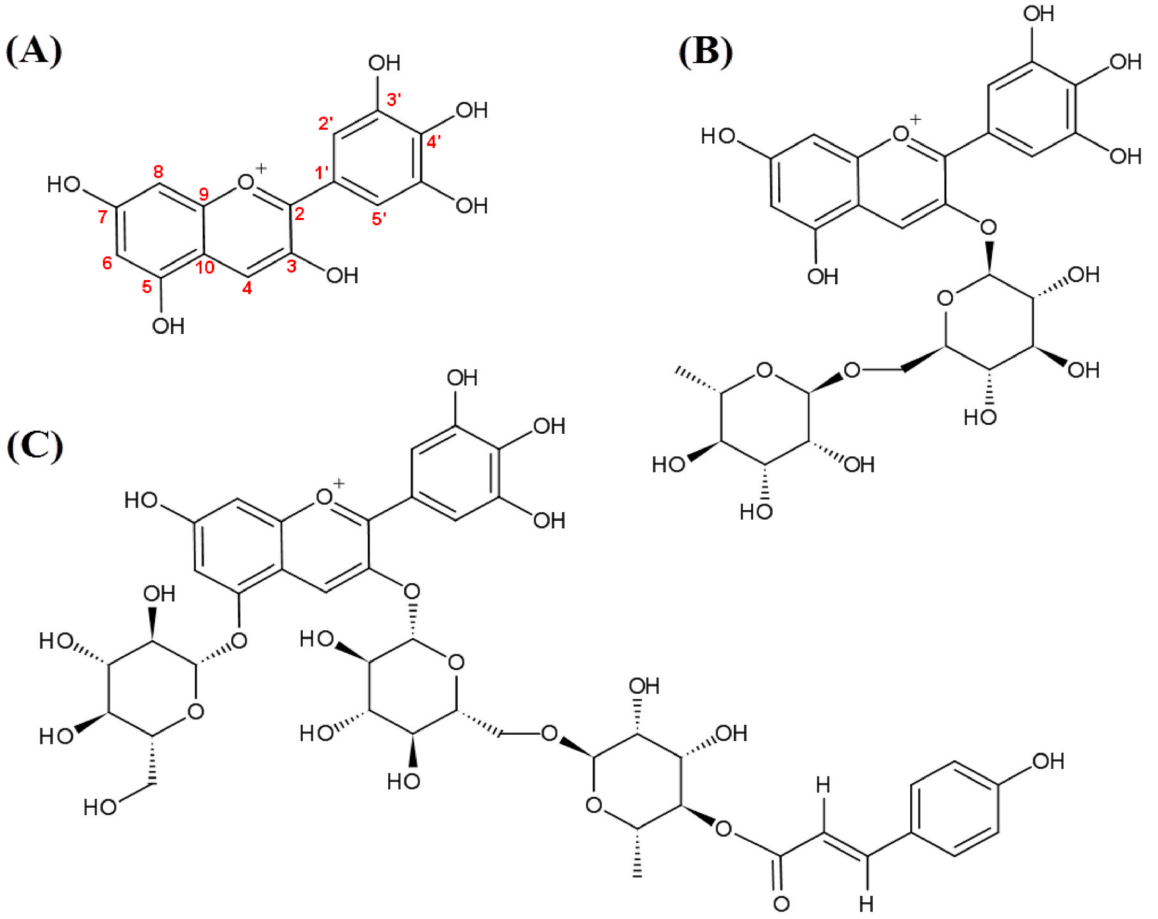

Fig. 1. Chemical structures of (A) delphinidin anthocyanidin, (B) delphinidin-3-rutinoside and (C) delphinidin-3-(*p*-coumaroylrutinoside)-5-glucoside (nasunin).

homogalacturonan, rhamnogalacturonan I (RG-I) and rhamnogalacturonan II (RG-II). In some cases, other blocks such as xylogalacturonan and apiogalacturonan are also observed (Christiaens et al., 2016). Homogalacturonan, also known as the "smooth region", accounts for approximately 60–70% of the pectin structure. This block is constructed of (1 → 4) bonded α-D-galacturonic acid (GalA) units, in which some of the units' C-6 linked carboxyl groups are methyl-esterified (Mellinas et al., 2020). The second most abundant domain in the structure of pectin is RG-I, also known as the "hairy region", which accounts for approximately 20–35% of the pectin structure. The backbone of this block is constructed of L-rhamnose and GalA units, in the form of the repeating disaccharide $[(\rightarrow 4)\text{-}\alpha\text{-D-GalA-}(1 \rightarrow 2)\text{-}\alpha\text{-L-Rhamnose-}(1\rightarrow)]_n$. The GalA units in this block could be acetylated or methylated at C-2 and C-3 and a large number of rhamnose units are substituted at C-4 by neutral sugar side chains of arabinans, galactans and arabinogalactans. These side chains are largely composed of α-L-arabinose and β-D-galactose (Maxwell et al., 2012). RG-II, the third and most complex structural domain that accounts for approximately 10% of pectin structure, is composed of a homogalacturonan backbone with at least 8 units of GalA, in which some of the units' C-6 linked carboxyl groups might be methyl-esterified. This backbone is substituted with side branches that are constructed from sugars such as rhamnose, xylose, galactose, fucose, apiose and aceric acid, with more than 20 different types of linkages (Christiaens et al., 2016; Mellinas et al., 2020).

Extracted pectin from various plants is different in some structural characteristics, such as degree of esterification (DE), polymer size distribution, the nature and position of the neutral sugar side chains and acylation pattern (Wusigale et al., 2020). Furthermore, the extraction method could also significantly affect the pectin structure. However, the most profound factors for functional differentiation of various pectic polysaccharides are GalA content and DE. FAO mandates that in order to be included in E440 as a food additive, industrial pectic polysaccharides must have at least 65% polygalacturonic acids in their structure (Maxwell et al., 2012), which highlights the importance of GalA content in this regard. DE is another crucial parameter, which is defined as the percentage of esterified carboxyl groups in the structure of pectin (Mellinas et al., 2020). This factor is commonly used for the classification of pectic polysaccharides and indicates the gelling, texturizing and emulsifying properties of this compound. Based on DE, pectin is classified into two groups of high methoxyl pectin (HMP, DE > 50%) and low methoxyl pectin (LMP, DE ˂ 50%) (Kazemi et al., 2019b).

The structures of eggplant peel pectin (EPP) and eggplant calyx pectin (ECP) are reported to have 66.8–69.7% and 60.2% GalA, respectively. The most abundant neutral monosaccharide in the structure of EPP is galactose (18.1%), followed by rhamnose (8.8%), arabinose (2.8%), xylose (1.3%) and fructose (0.7%), while in the case of ECP, arabinose is the main neutral monosaccharide (27.8%), followed by rhamnose (7.4%), galactose (2.3%), xylose (0.7%) and fructose (0.4%). This could indicate that the most common side chains in the RG-I block of EPP and ECP are galactans and arabinans, respectively. Furthermore, the presence of xylose and fructose could point to the existence of RG-II blocks in the structure of both EPP and ECP. The molar ratios of homogalacturonan and RG-I in EPP are nearly 58.6% and 38.5%, respectively, which means that this polysaccharide is composed of a nearly linear structure. ECP, on the other hand, illustrates molar ratios of 52.8% and 44.9% for homogalacturonan and RG-I, respectively, which means that it contains high levels of hairy regions in its structure. Furthermore, based on the value of (Arabinose + Galactose)/Rhamnose, it is estimated that attached side chains to the RG-I portion of EPP ((Arabinose+Galactose)/Rhamnose = 2.375) are shorter than ECP ((Arabinose+Galactose)/Rhamnose = 4.067) (Kazemi et al., 2019a; 2019b).

EPP and ECP are classified as HMP with reported DE of approximately 60.2–68.18% and 60.74%, respectively. Furthermore, EB, especially EP, is one of the highest yielding agricultural by-products regarding the extraction of pectin. The extraction yield of pectin from EP and EC using different extraction methods is reported to be in the optimum range of 26.10–33.64% and 18.36%, respectively. (Kazemi et al., 2019a; 2019b; 2019c). In comparison with the extraction yields from other high-yielding sources, such as citrus peel (~5–26%), tomato by-products (~10–35%) and passion fruit peel (~7–30%) the EP illustrates a promising potential in this regard (Marić et al., 2018).

3.3. Pullulan

Pullulan is a linear exo-homopolysaccharide that is produced through submerged fermentation method by various strains of yeast-like microorganism, *Aureobasidium pullulans*. This neutral, water-soluble and GRAS polymer is a commercially important product with a variety of applications in the food, cosmetic, textile and pharmaceutical industries. The structure of pullulan is mainly composed of repeating units of α (1 → 6) linked maltotriose units. In some cases, repeating units of panose and isopanose are also found in pullulan partial acid hydrolysis (Singh et al., 2019).

EB could be utilized as a carbon source for production of pullulan through fermentation process; however, there are a few potential drawbacks related to this case. For example, the pectin in the structure of plant cell wall could limit the access of hydrolytic enzymes to cellulose molecules. Furthermore, EB contains high amounts of phenolic compounds, which could exert anti-microbial effects on *A. pullulans* (Talekar et al., 2018). Nevertheless, a method for production of pullulan from EB through integrated valorization has been documented, in which the pectin and phenolic compounds are initially extracted and then, as an approach to zero-waste valorization, the leftovers are subjected to enzymatic hydrolysis and microbial fermentation for pullulan production. Based on this method, the production yield of pullulan from EB was reported at 16.8 g/L. Furthermore, Obtained pullulan demonstrated α(1 → 6) and α(1 → 4) glucoside bonds (indicative of repeating maltotriose units), acceptable ash and protein contents (~1.8% and ~2.1%, respectively) and chemical characteristics similar to the commercial pullulan (Kazemi et al., 2019c).

4. Functional and biological properties of bioactive compounds

4.1. Anthocyanins

In a review study published by Gürbüz et al. (2018), valuable phytochemicals and health benefits of eggplant are thoroughly discussed. This section has focused on the biological activities of anthocyanins, the most dominant phenolic compounds in EB, with a special emphasis on delphinidin anthocyanidin and delphinidin glucosides. Anthocyanins are associated with several substantial biological properties, with the most important one being the antioxidant potential.

Reactive oxygen and nitrogen species (ROS and RNS) are two natural products created by mitochondria during normal cellular metabolism for several purposes, for instance, cytotoxicity against hazardous pathogens (Tena et al., 2020). However, these molecules are also perfectly capable of damaging normal cells, therefore, maintaining a balance between these species and antioxidants is critical for cell survival. If this balance becomes disrupted by the overproduction of these species, a phenomenon known as oxidative stress will occur. During this phenomenon, normal cells such as proteins, lipids and DNA molecules could be damaged by ROS and RNS, which might lead to complications such as cancer, cardiovascular and neurodegenerative diseases. Therefore, reactive species are usually neutralized or recycled after they are produced, and the cell performs this function by utilizing antioxidant enzymes, which are produced by the cell itself, or natural antioxidants such as anthocyanins, which are acquired through diet (Fallah et al., 2020; Zhao et al., 2014). However, the undesirable effects of ROS are not exclusive to living cells. Many food products are also susceptible to oxidation due to the production of free radicals, which could decrease the food quality by producing off-flavors, off-colors and off-odors. Hence, the presence of anthocyanins in food products could neutralize free radicals and improve the shelf life of food and beverages (Horincar, Enachi, Bolea, et al., 2020). Generally, the capability of antioxidants in donating hydrogen atoms or electrons and scavenging free radicals defines their antioxidant potential. Some antioxidants are also capable of chelating metal ions and subsequently, preventing them from engaging in redox reactions. The antioxidant power of anthocyanins is relevant to a concept known as the structure-activity relationship (Zhao et al., 2014). Based on this concept, the antioxidant activity of anthocyanins depends on their glycosylation and acylation patterns, the number of hydroxyl and methyl groups in their structure, and catechol moiety and oxonium ion in their B and C rings, respectively (Fallah et al., 2020). It is reported that among six common anthocyanidins found in nature, delphinidin possesses the highest antioxidant potential (Yang et al., 2011). The number of –OH groups of this molecule surpasses other anthocyanidins, which could be a reason for higher antioxidant potential of this compound. Furthermore, the presence of o-di-hydroxyl group in the B-ring of delphinidin, cyanidin and petunidin enables these compounds to form complexes with metal ions, which could contribute to their antioxidant activity; however, it also makes them more susceptible to oxidation (Castañeda-Ovando et al., 2009). The effect of glycosylation on antioxidant potential is still not definitive, since several studies suggest disputed results (Yang et al., 2011). However, the structure of linked sugars might affect the antioxidant potential of anthocyanins. In the case of major eggplant anthocyanins, attached sugars in both delphinidin-3-rutinoside and delphinidin-3-(*p*-coumaroylrutinoside)-5-glucoside could act as antioxidants and further enhance the antioxidant potential of those anthocyanins, comparing to an unsubstituted delphinidin aglycone. In comparison with most other antioxidants, anthocyanins illustrate a much higher antioxidant potential as a consequence of their exceptional structure. For example, results from oxygen radical-absorbing capacity analysis illustrates that the antioxidant capacity of 3-glucosides of delphinidin, malvidin and petunidin are 3–6 times higher, comparing to Trolox standard. It was also observed that by employing ferric reducing ability analysis, antioxidant power of mentioned anthocyanins was 2–2.5 times higher than ascorbic acid (Turturică et al., 2015). In regards to eggplant peel extract (EPE), which is the most common utilization form of EB phenolic compounds, antioxidant activity usually follows a linear trend with total phenolic content (TPC), which is directly affected by eggplant cultivar and ripening stage, as well as the extraction method and conditions (Chatterjee et al., 2013).

Another remarkable attribute of anthocyanins is the antimicrobial potential of these compounds. Anthocyanins are capable of inhibiting microbial populations through several mechanisms, such as destabilizing cytoplasm membrane, permeabilizing plasma membrane and destroying the cell wall and intercellular matrix (Cisowska et al., 2011). Anthocyanins could also interfere with microbial metabolism, by directly rendering some substrates unavailable to them or affecting intra- and extra-cellular microbial enzymes in several ways (Niño-Medina et al., 2017). Some anthocyanins are also capable of disrupting the adhesiveness of microbial cells to body cells, which is, for many pathogens, the prerequisite for colonization and infection (Gato et al., 2020). Anthocyanins have been proven beneficial in the case of food-borne pathogens (Khoo et al., 2017), which makes them ideal for food preservation (Gong et al., 2021) and the development of food packaging (Alizadeh-Sani et al., 2021). In the case of delphinidin, this anthocyanin was patented to treat *Staphylococcus aureus* infections (Roewer & Broscheit, 2013). Furthermore, a significant number of studies obtained promising results regarding the application of delphinidin glycosides, along with other anthocyanins in the form of extracts on a vast range of microorganisms, most notably *Escherichia coli*, *Pseudomonas aeruginosa*, *Salmonella enterica serovar Typhimurium*, *Serratia marcescens*, *Listeria monocytogenes*, *Listeria innocua*, *Enterococcus faecium*, *Staphylococcus aureus*, *Aeromonas hydrophila*, *C.violaceum*, etc. (Cisowska et al., 2011; Santos et al., 2020; Tena et al., 2020).

Anthocyanins have also been extensively studied in regards to cancer therapy. (Wu et al., 2020). They could affect the prevention and treatment of cancer through various pathways, such as Free-radical scavenging, Cyclooxygenase, Mitogen-activated protein kinase and inflammatory cytokines signaling (Khoo et al., 2017). Studies showed that anthocyanins could be effective on several types of gastrointestinal cancers (Dharmawansa et al., 2020), skin cancer (Diaconeasa et al., 2020), prostate cancer (Costea et al., 2019) and breast cancer (Iqbal et al., 2018). Delphinidin, in particular, has induced apoptosis and autophagy in HER-2 positive breast cancer cells (Chen et al., 2018). The anti-metastatic effect of this compound on colorectal cancer cells has also been demonstrated (Huang et al., 2019). In the case of hepatocellular carcinoma cells (liver cancer), delphinidin has been proven effective at inhibiting Epithelial-to-mesenchymal transition by inhibiting several signaling pathways (Lim et al., 2019). It also demonstrated preventive effects on ovarian clear cell carcinoma by inactivating PI3K/AKT and ERK1/2 MAPK pathways (Lim et al., 2016). The anticancer effects of delphinidin and its glycosides have also been demonstrated in other studies (Han et al., 2019; Kuo et al., 2019; Mazewski et al., 2019).

It could be stated that the antioxidant, antimicrobial and anticancer effects are the main biological functions of anthocyanins. However, these compounds have also proven beneficial in prevention and treatment of other health-related complications, such as diabetes (Oliveira et al., 2020), stroke (Manolescu et al., 2019) and inflammation (Speer et al., 2020).

4.2. Pectin

The importance of pectin in food and pharmaceutical industries as a gelling, thickening, coating and stabilizing agent is well established (Maxwell et al., 2012; Mellinas et al., 2020). However, there are several functional properties that significantly influence the applicability of pectin in food and pharmaceutical products.

Water holding capacity (WHC) is one of the most important functional attributes of pectic polysaccharides. It is defined as the amount of water that a material can retain in its structure against natural and/or synthetic forces (for instance, an applied shear stress). This factor plays a crucial role in technological aspects of utilization of pectin since it directly affects the gelling and texturing properties of this compound (de Moura et al., 2017). WHC of EPP is measured around 6.1 g/g of pectin (Kazemi et al., 2019b), which is higher than commercial apple pectin (2.00 g/g) (Rubio-Senent et al., 2015), pistachio green hull (4.1 g/g) (Kazemi et al., 2019d) and *Opuntia ficus indica* cladodes (5.42 g/g) (Bayar et al., 2018); and lower than commercial citrus pectin (10.35 g/g) (Rubio-Senent et al., 2015). WHC of ECP is also measured around 4.62 g/g of pectin. However, these values are not definitive and could vary based on several physical, chemical and environmental factors. For example, Other than temperature, pH and ionic strength of the medium, WHC is also affected by structure, chemical composition and porosity of the employed pectic polysaccharide (Kazemi et al., 2019b).

Similar to WHC, oil holding capacity (OHC) is another important functional factor regarding the utilization of pectin. The definition is the same as WHC, which is the amount of oil that a material can retain per unit of weight. This attribute could affect emulsifying and stabilizing properties, therefore, pectic polysaccharides with high OHC could be utilized for stabilizing emulsions and high-fat food products by facilitating the solubilization or dispersion of two immiscible liquid phases (Rubio-Senent et al., 2015). OHC of EPP is measured around 2.36 g/g (Kazemi et al., 2019b), which is nearly the same as commercial apple and citrus pectin (2.22 and 2.59 g/g, respectively) (Rubio-Senent et al., 2015) and higher than *Opuntia ficus indica* cladodes pectin (1.23 g/g) (Bayar et al., 2018) and pistachio green hull pectin (2.02 g/g) (Kazemi et al., 2019d). OHC of ECP is also measured around 1.46 g/g. Similar to WHC, OHC is also affected by structural, chemical and environmental factors. For example, DE and DM, two prominent factors in determining the hydrophobicity of pectin, could have a notable effect on OHC (de Moura et al., 2017).

Based on evaluation of emulsifying properties, the emulsifying activity of EPP and ECP at the temperature of 24 °C is reported to be around 57.16% and 50.85%, respectively (Kazemi et al., 2019b). The measured value for EPP was nearly the same as pistachio green hull pectin (58.3%) (Kazemi et al., 2019d), but higher than *Citrus medica* peel pectin (46.5%) (Pasandide et al., 2017) and sour orange peel pectin (40.7%) (Hosseini, Khodaiyan, & Yarmand, 2016). Furthermore, emulsions that were prepared using EPP and ECP displayed a very good emulsion stability over the periods of 1 and 30 days at the temperatures of 4 °C and 24 °C. Other than environmental factors, parameters such as concentration, average molecular weight and GalA content could also significantly affect the emulsifying properties of this compound (Bayar et al., 2017).

Generally, foaming properties of pectin are of less importance in the food industry, comparing to other functionalities of this compound. However, pectin with improved foaming attributes could be employed in various food products, such as aerated foods; and eggplant pectin presents much better foaming properties, compared to many other pectin sources. Evaluation of foaming capacity and foam stability of EPP and ECP showed that increasing the concentration of pectin from 2% w/v to 4% w/v, improves the foaming properties of the solution; and EPP illustrates better functionality than ECP in this matter (Kazemi et al., 2019b). One factor that could directly affect the foaming properties is the surface tension of the solution. It was observed that increasing the concentration of EPP and ECP results in a reduction of the surface tension, which could lead to improved foaming properties of the solution. The reason for the surface tension reduction could be attributed to the high TPC of eggplant pectin. Some phenolic compounds can accumulate in the air-water interface and increase the surface pressure, which results in the reduction of surface tension (Di Mattia et al., 2010). The relationship between the amount of phenolics and surface tension of the solution could also justify the better foaming properties of EPP, comparing to ECP.

In comparison with many other sources of pectin, Eggplant by-products pectin (EBP) illustrates a great potential regarding the antioxidant activity. Regardless of the extraction method, eggplant pectin offers a significant antioxidant potential and low values of 50% inhibitory concentration (IC_{50}) of free radicals. Kazemi et al. (2019a) calculated the IC_{50} value of EPP to be around 1.39 mg/ml, which illustrates the great antioxidant potential of this substance. In general, pectic polysaccharides illustrate an intrinsic antioxidant potential, which depends on galacturonic acid content, molecular weight and degree of methylation (Bayar et al., 2018). Furthermore, it is possible for plant protein molecules to be linked with the extracted pectin and therefore, enhance its antioxidant capacity. However, the most important reason for the high antioxidant activity of EBP is their considerable content of phenolics, which is also the reason why EPP has much higher antioxidant potency (DPPH: ~90% at the concentration of 10 mg/mL) than ECP (DPPH: ~50% at the concentration of 10 mg/mL) (Kazemi et al., 2019b).

Other than antioxidant potential, pectin has been linked to other biological properties, such as anti-inflammatory and anti-tumor activities (Maxwell et al., 2012). Although the EBP has not been studied in these subjects, given its promising biological properties, it seems much needed for shortcomings in this regard to be addressed.

4.3. *Pullulan*

As described before, unlike pectin and anthocyanins which are extracted from EB, pullulan is produced through fermentation by *A. pullulans* and EB is used as a carbon source in this process. Therefore, it could be stated that the functional properties of obtained pullulan are nearly identical and much more influenced by the microorganism and fermentation conditions, rather than the employed carbon source.

Contrary to what was discussed earlier about pectin, pullulan does not offer strong features in regards to some functional properties such as OHC, emulsifying properties and foaming capacity, since it is a highly hydrophilic polymer and lacks hydrophobic substitutions. However, one of the great advantages of pullulan is the presence of multiple reactive sites in its structure, which could be subjected to chemical modification. In a review study conducted by Tiwari et al. (2019), various strategies for derivatization and modification of pullulan have been discussed. Regarding the mentioned functional properties, Omar-Aziz et al. (2020) performed a study, in which pullulan was chemically modified with octenyl succinic anhydride to improve its surface activity, emulsifying properties and foaming capacity. Results from this study demonstrated that the surface tension of an unmodified pullulan solution, with a concentration of 0.5% w/w, was measured at 68.23 mN/m. However, it was observed that the surface tensions of modified pullulan solutions with degree of substitution (DS) of 0.020 and 0.061 was decreased to 53.31 Nm/m and 37.77 Nm/m, respectively. The same pattern was also observed in regards to interfacial tension (24.53, 16.93 and 7.83 mN/m for untreated pullulan, pullulan with DS of 0.020 and 0.061, respectively). Furthermore, the assessment of emulsifying properties showed that the unmodified pullulan offered no emulsifying capacity (0.00%), while this parameter was measured at 100% for both modified pullulans; also, both of them illustrated more than 92% of emulsion stability after 30 days. Unmodified samples also showed no foaming capacity, while this factor was measured at 60.67% and 124% for pullulans with DS of 0.020 and 0.061, respectively. After 30 min of storage at 28 ± 2 °C, foam stability for pullulans with DS of 0.020 and 0.061 was measured at 52.38% and 66.99%, respectively. Therefore, it could be concluded that with appropriate modifications, pullulan could even be employed in systems with requirements that are not available in an unmodified pullulan sample.

Regardless of the mentioned properties, unmodified Pullulan offers some extraordinary characteristics that qualify this substance to be utilized in the food and pharmaceutical sectors, which will be discussed in the application section.

5. Valorization methods

The literature regarding the extraction of bioactive compounds from EB has been summarized in Table 2, into three sections: conventional approach, emerging techniques and zero-waste valorization approach.

5.1. *Conventional approach (solid-liquid extraction)*

The most common method for extraction of bioactive compounds from EB is solid-liquid extraction (SLE) (sometimes it is referred to as solvent extraction). In this approach, the target tissue is soaked in solvent to extract the desired substance. SLE is simple and usually requires no specific equipment, however, high solvent consumption and relatively long extraction durations could be some of the drawbacks of this approach (Silva et al., 2017).

Extraction of anthocyanins from EB by SLE is directly affected by several factors such as solvent type, pH, temperature, extraction time, tissue size, liquid/solid ratio and shaking or rotating speed (most of these factors affect other extraction methods as well). Polar solvents such as ethanol, methanol and acetone have been commonly used for extraction of anthocyanins from EB. The use of other solvents, such as acidified water (Ferarsa et al., 2018), organic acids (Todaro et al., 2009) and glycerol mixtures (Manousaki et al., 2016; Philippi et al., 2016) has also been reported. Most of the studies have employed a combination of different solvents and water, with various ratios. Ferarsa et al. (2018) reported that compared to pure ethanol or water, utilization of 50% ethanol increased the extraction yield of EP anthocyanins. They argued that in a binary solvent system of ethanol and water with a suitable ratio, the difference in polarity of solvents could maximize the solubility of all compounds. Doulabi et al. (2020) and Dranca and Oroian (2016) also reported the same pattern in this regard. Furthermore, it is reported that the pH of solvent noticeably affects the extraction yield of EP

Table 2
Extraction and production methods of bioactive compounds from eggplant by-products.

Substance	Method	Sample preparation	Solvents	(Optimum) Process conditions	Yield[a]	References
Conventional approaches						
Anthocyanins	SLE	Peel (cut to 20 mm^2)	(1): 1.25% Tartaric acid (2): 1.25% Malic acid (3) Acidified ethanol	T: 40 °C, time: 60–80 min, LSR: 10 ml/g	TA: 65.79–76.44 mg/100 g FW	Todaro et al. (2009)
Anthocyanins	SLE	Peel (grounded)	0.15% HCl in acetone -aqueous acetone (30:70 v/v) with 0.15% of HCl	T: 4 °C, time: 4 h, LSR: 4:1	EY: 2.3 g/100 g FW	Hernández-Herrero and Frutos (2011)
Anthocyanins	SLE	Peel (shredded and lyophilized)	Water-ethanol (1:1) in 10% citric acid	T: 60 °C, time and LSR: N/A	TA: 19.75 g/kg DW	Chatterjee et al. (2013)
Anthocyanins	SLE	Peel (dried at 40 °C and grounded)	(1): 70% methanol with 0.2% formic acid (2): 70% ethanol with 0.2% formic acid (3) 70% acetone with 0.2% formic acid	T: room, time: 40 m, LSR: N/A	TA: 51.56–82.83 mg/100 g DW	Boulekbache-Makhlouf et al. (2013)
Flavonoids	SLE	Peel (stored in the dark at 4 °C)	Glycerol-ammonium acetate (3:1)	T: 80 °C,time: 3 h LSR: 100 ml/g	Total flavonoids: 24.68 mg/g DW	Manousaki et al. (2016)
Anthocyanins	SLE	Peel (chopped)	Water/ethanol/citric acid (50:48:2)	T: room, time: 60 min LSR: 15 g/100 ml	TA: 115.43 mg/100 g FW	Hosseini, Gharachorloo, et al. (2016)
Phenolic compounds	SLE	Peel (Grounded)	Acidic water with pH 2	T: 75 °C, time: 60 min LSR: 10:1	TPC: 23.101 mg/g DW	Ferarsa et al. (2018)
Anthocyanins	SLE	Peel (Crushed and dried)	50% ethanol with 2.5% HCL (v/v)	T: 65 °C, time: 3 h, LSR: 50:1	EY: 38.6 g/100 g DW TA: 431 mg/100 g DW	Akhbari et al. (2019)
Emerging approaches						
Anthocyanins	SFE	Peel (shredded and lyophilized)	CO$_2$	CO$_2$ flow rate: 2 L/min, pressure: 10 MPa, T: 60 °C, time: 90 min LSR: 18:1	TA: 17.04 g/kg DW	Chatterjee et al. (2013)
Phenolic compounds	UAE	Peel (dried at 70 °C and pulverized)	(1): water/glycerol 90% (2): water/ethanol 40%	UP: 140 W, F: 37 kHz, time: 90 min, T and LSR: (1): 50 °C and 100 ml/g, (2) 80 °C and 82 ml/g	TPC: 13.40–13.51 mg/g DW	Philippi et al. (2016)
Phenolic compounds	UAE	Peel (dried at 40 °C and powdered)	(1): 76.6% methanol (2): 54.4% methanol	F, T and time: (1):33.88 kHz, 69.4 °C and 57.5 min; (2): 37 kHz, 55.1 °C 44.85 min	(1): TPC: 29.63 g/100 g extract FW (2): TA:2410.71 mg/100 g extract FW	Dranca and Oroian (2016)
Anthocyanins	UAE	Peel (dried at 40 °C and powdered)	(1): Ethanol (2): Methanol (3): 2-propanol	LSR: 10 ml/g F, T and time: (1): 28.8 kHz, 67.1 °C and 49.5 min, (2): 45 kHz, 50 °C and 53.75 min (3): 30.6 kHz, 70 °C and 60 min	TA: (1): 0.69 g/kg (2): 0.68 g/kg (3): 1.71 g/kg	Dranca and Oroian (2017)
Phenolic compounds	UAE	Peel (cut to 1 × 1 cm^2)	Acidified water	UP: 400 W, F:12 KHz, T: room, time: 30 min, LSR: 10:1	TPC: 29.011 mg/g DW	Ferarsa et al. (2018)
Anthocyanins	UAE	Peel (dried at 40 °C)	70% ethanol	UP:100 W, F: 40Khz, T: 40°, time: N/A, LSR: 20 ml/g	TA: 0.58 mg/g DW	Condurache et al. (2019)
Anthocyanins	MAE	Peel (dried at 30 °C)	73.49% ethanol with pH 3.06	MP: 269.82 W, time: 7.98min, LSR: 5.01 ml/g	EY: 3.27% TA: 6.99 mg/L	Doulabi et al. (2020)
Pectin	UAE	Peel (dried at 45 °C and milled)	Acidified water with pH of 1.5	UP: 50 W, T: room, time: 30 min, LSR: 20:1	EY: 33.64 g/100 g DW	Kazemi et al. (2019a)
Pectin	MAE	(1): Peel (dried at 45 °C and powdered) (2): Calyx (dried at 45 °C and powdered)	Acidified water with pH of 1.5	MP: 700 W, T: room, time: 2 min, LSR: 20:1	EY: (1): 29.17g/100 g DW (2): 18.36 g/100 g DW	Kazemi et al. (2019b)
Zero-waste approach						
Pectin and phenolic compounds	SLE	Peel (dried at 50 °C and grounded)	Acidified water with pH of 2.5	T: 90 °C, time 90 min, LSR: 40 mg/L	EY of pectin:: 26.1 g/100 g DW EY of phenolics: 20.2 g/100 g DW	(Kazemi et al., 2019c)
Pullulan	Fermentation	Leftovers from extraction of pectin and phenolics (dried at 45 °C, powdered)	Enzymatic hydrolysate of the leftovers (3% w/v) with pH of 5	Fermentation processes: Medium: 50 mL of enzymatic hydrolysate with pH 5.5, supplemented with 5 g/L of KH$_2$PO$_4$, 1 g/L of NaCl, 0.6 g/L of (NH$_4$)$_2$SO$_4$, 0.5 g/L of MgSO$_4$·7H$_2$O, 0.01 g/L of ZnSO$_4$, 0.01	Production yield: 16.8 g/L	

(*continued on next page*)

Table 2 (*continued*)

Substance	Method	Sample preparation	Solvents	(Optimum) Process conditions	Yield[a]	References
Conventional approaches						
				g/L of $MnSO_4$, 0.01 g/L of $FeSO_4$ and 4 g/L of yeast extract and 5% (v/v) of inoculum T: 28 °C, time: 7 days		

FW: fresh weight, DW: dry weight, TA: total anthocyanins, EY: extraction yield TPC: total phenolic content, MP: microwave power, UP: ultrasound power, F: frequency, SLE: solid lipid extraction, SFE: supercritical fluid extraction, UAE: ultrasound assisted extraction, MAE: microwave-assisted extraction.

[a] Amounts of yield are reported according to each study's definition of this parameter.

anthocyanins (Ferarsa et al., 2018), therefore, most of the studies have used HCL or citric acid to lower the pH. Anthocyanins are very sensitive to pH changes. They are easier to extract and more stable at acidic pH and usually start degrading at alkaline mediums (Dranca & Oroian, 2016). These compounds are also greatly affected by the applied temperature. Most literatures recommend temperatures between 40 and 75 °C as optimum for extraction of anthocyanins from EP. Todaro et al. (2009) reported an increase in extraction yield by increasing the temperature up to 40 °C, however, the yield started to decline when the temperature was further increased. Ferarsa et al. (2018) reported that the highest extraction yield of anthocyanins was measured at 75 °C. It is worth mentioning that the effect of temperature (and other mentioned parameters) cannot be solely analyzed and it must be considered along with other extraction factors. For example, extraction time, along with temperature, could have a profound effect on measured yield, since exposure to high temperatures during prolonged extraction times could degrade a good portion of extractable anthocyanins. Extraction time, along with three other parameters of tissue size, liquid/solid ratio and shaking or rotating speed are mostly associated with mass transfer principles (Silva et al., 2017). It has been reported that ground EP offered a higher extraction yield comparing to square slices, since ground particles offer a larger surface area and improved levels of solvent and solute diffusivity (Ferarsa et al., 2018). Liquid/solid ratio is another influential parameter that must be optimized in order to simultaneously achieve desirable extraction yields and lower levels of solvent consumption (Todaro et al., 2009). Additional information regarding the extraction of phenolics from EB are provided at Table 2.

5.2. *Emerging methods*

Over the past two decades, as a result of growing interest and demand for bioactive compounds, scientists have strived to develop novel and more efficient techniques for extraction of these substances. These new methods have mostly focused on the improvement of several areas, such as improvement of extraction time and yield, reduction of solvent consumption, employment of green and GRAS solvents and simplification of concentration and purification steps (Dranca & Oroian, 2016; Silva et al., 2017). The result of these efforts was the development of various techniques such as ultrasound and microwave-assisted extraction (UAE and MAE), supercritical fluid extraction (SFE), pulse electric field extraction and Ohmic heating-assisted extraction, some of which have been used for the extraction of bioactive compounds from EB.

Several studies have employed UAE to obtain phenolic compounds and pectin from EB. The advantages of UAE are the consequences of a mechanism known as the acoustic cavitation phenomenon. Formation, growth and collapse of air bubbles by ultrasound frequencies in the extraction medium exerts a substantial amount of mechanical energy toward plant tissue, which leads to the enlargement of cell pores or cell wall rupture. This incident increases the contact surface between solvent and tissue and facilitates the access of solvent to the target compound and subsequently, improves the extraction mass transfer rate. Cavitation also increases the temperature in the location of bubble collapse, therefore, affecting the mass transfer by improving the solubility of the target compound in the surrounding solvent (Chemat et al., 2017; Kumar et al., 2021). Other than conventional factors that were mentioned in section 5.1, UAE process is also affected by ultrasound power, frequency and duration. Dranca and Oroian (2016) employed UAE and reported an increase in extraction yield of phenolic compounds from EP, comparing to previous studies with conventional extraction methods. They also found out that ultrasonic frequency, along with temperature and time had a significantly positive linear effect on the amount of TPC. Ferarsa et al. (2018) performed a comparison between SLE and UAE in regards to anthocyanin extraction from EP and reported extraction yields of 23.101 mg gallic acid equivalent (GAE)/g and 29.011 mg GAE/g for SLE and UAE, respectively. Several other studies have highlighted the benefits of UAE for extraction of phenolics from EB (Table 2). Kazemi et al. (2019a) utilized UAE for extraction of pectin from EB. They obtained a desirable yield of 33.64% by applying an ultrasound power of 50 W, however, it was observed that increasing the ultrasound power from 50 W to 150 W led to a decrease in extraction yield of pectin. They argued that the generated energy from cavitation might have degraded the pectin structure into smaller pectic fractions such as pectic-oligosaccharides and subsequently, affected the extraction yield. It was also reported that the increase of extraction time and reduction of pH had a positive effect on extraction yield of pectin.

MAE is another emerging method that has been used for extraction of phenolics and pectin from EB. Microwave is an electromagnetic wave, which means that it is composed of electric and magnetic fields that oscillate to each other in a frequency range between 300 MHz and 300 GHz. This wave has the ability to penetrate into certain materials and affect polar molecules through two mechanisms of ionic conduction and dipole rotation, which subsequently generate a considerable amount of heat. When microwave enters plant cells, it evaporates the water molecules inside the cell. This phenomenon generates an intense pressure inside the cells and eventually induces cell rupture, which leads to increased contact surface between solvent and tissue and the improvement of mass transfer rate (Ekezie et al., 2017). Doulabi et al. (2020) used MAE for extraction of EB phenolics and reported that increasing the microwave power from 100 W to 300 W led to an improvement of extraction yield. Furthermore, Kazemi, et al. (2019b) employed this technique for extraction of pectin from EP and EC and recorded the extraction yields of 29.17% and 18.36%, respectively.

In another attempt for utilization of emerging extraction technologies, Chatterjee et al. (2013) compared SLE and SFE methods for extraction of anthocyanins from EP. They reported that an increase in the extraction pressure from 10 MPa to 15 MPa resulted in the reduction of extraction yield. Furthermore, the comparison between the two methods showed that the SLE, with the extraction yield of 19.75 g/kg presented a higher efficiency, comparing to SFE with the yield of 17.04 g/kg.

5.3. *Zero-waste valorization approach*

Many of the agro-industrial by-products have the potential to yield several value-added compounds upon valorization. Therefore, the development of methods based on integrated valorization of these by-products could be beneficial from both economic and environmental perspectives. In the case of EB, Kazemi, et al. (2019c) proposed a zero-wastes approach for simultaneous recovery of pectin and polyphenols and production of pullulan from EP. In this technique, EP is initially subjected to an SLE method that is co-optimized to obtain the highest possible yields of pectin and polyphenol extraction. At the end of the extraction process, the aqueous extract is subjected to purification steps in order to acquire pectin and polyphenols and the solid leftovers are subjected to enzymatic hydrolysis using cellulase enzyme. The acquired hydrolysate is then utilized as a carbon source for the production of pullulan through fermentation process using *A.Pullulans*. The solid leftovers, which are usually discarded at the end of other extraction approaches, contain high amounts of cellulose. Furthermore, the phenolics and pectin, which have the potential to prevent microbial growth and disrupt the access of hydrolyzing enzymes to cellulose molecules in plant cell walls, respectively, are separated from these leftovers (Talekar et al., 2018). Therefore, in the proposed zero-waste approach, the leftovers could be utilized efficiently as a carbon source for the production of pullulan. The details of this approach are summarized in Table 2. Moreover, Fig. 2 illustrates the differences between zero waste approach and other valorization approaches of EB.

6. Applications of bioactive compounds

6.1. Phenolic compounds

Up until now, most of the research body concerning the utilization of EB bioactive compounds is focused on the use of extracted phenolic compounds from the peel of eggplant. This extract is mainly employed as a colorant and antioxidant agent in food and pharmaceutical products. Horincar, Enachi, Bolea, et al. (2020) used EPE in order to improve the biological value of lager beer since the beer antioxidants are prone to degradation during technological practices, such as boiling, clarification, filtration, etc. Furthermore, higher antioxidant potential could diminish the production of *trans*-2-nonenal and other saturated and unsaturated aldehydes due to lipid oxidation, which could affect the beer flavor over time. They found out that the addition of 10 mg/mL of EPE increased the TPC of the beer samples by 43.73% and total flavonoid content by 106.02%, while it did not affect the extract, alcohol content, CO_2 content, or pH. Furthermore, upon the addition of EPE, the samples developed a reddish color and total monomeric anthocyanin content, which was not detectable before, was measured at 0.083 mg of delphinidin-3-glucoside equivalents/mL of beer. Antioxidant activity evaluation showed that the antioxidant potential slightly decreased after a 21 day storage period; however, it was still significantly higher in the

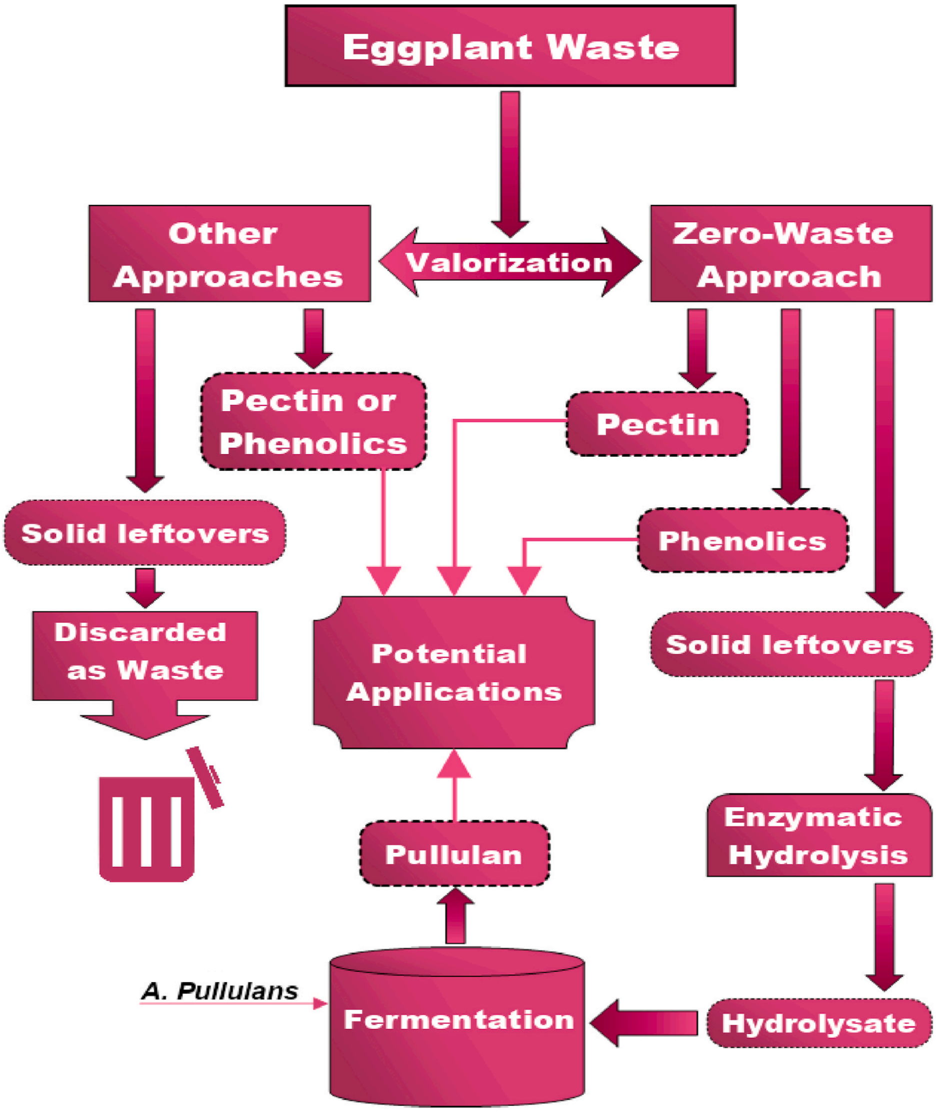

Fig. 2. A comparison between zero-waste approach and other approaches used to valorize eggplant by-products.

samples with EPE, compared to control samples. The overall results of this study demonstrated the successful application of EPE in the lager beer and could be a promising path for the usage of EPE in other beverages, as an alternative to artificial preservatives.

Chatterjee et al. (2013) studied the incorporation of solvent-extracted and CO_2-extracted EPE In jelly crystals and custard, as a model for non-thermal and thermal food applications, respectively. It was observed that the CO_2-extracted EPE contained significantly lower amounts of trace metals and was much more stable, compared to the solvent-extracted EPE. Regarding the food application study, both crystal jelly and custard presented characteristic odor and taste after treatment with EPE, without any off odor or unsavory aftertaste. In the case of product color, which was evaluated using lovebird color values, it was observed that the jelly crystals presented significant red shades upon the usage of both extracts, compared to the control sample. The treated custard with solvent-extracted EPE also displayed a red shade. However, the custard treated with CO_2-extracted EPE displayed a darker shade of the original golden yellow color of the custard. Results from this study suggested that the solvent-extracted EPE was more stable at high temperatures, while the CO_2-extracted EPE, which contained higher amounts of thermosensitive delphinidin-3-rutinoside, was more suitable for non-thermal food applications. In another study regarding the thermal behavior, Zhang, Sun, Wang, et al. (2020) evaluated the effect of different cooking methods, steaming and boiling, on degradation of EP anthocyanins. They used cookies prepared with a dietary fiber and anthocyanin dough as a model food. It was observed that as a result of thermal treatment, the amount of anthocyanins was decreased significantly in all samples; however, the steamed solid cookie showed better anthocyanin retention, compared to boiled cookies (which turned into paste as the result of boiling) and the control sample (a liquid phase containing only anthocyanins and not dietary fiber). The protective effect of dietary fiber on anthocyanins, especially in the steam solid samples, could be due to the entrapment of anthocyanins into the fiber matrix. Another possibility is the formation of interactions, such as hydrogen bonds, van der Waals forces, electrostatic interactions and hydrophobic interactions between the dietary fiber and anthocyanins, which might contribute to their thermo-stability. This study also observed that the steaming process was better for anthocyanin retention in solid samples, while boiling was preferable for liquid samples. The method of thermal treatment has a significant effect on the stability of eggplant phenolics, especially anthocyanins. Martini et al. (2021) studied the effect of four domestic cooking methods on the stability and bioaccessibility of eggplant phenolic compounds. In the case of anthocyanins, which are mostly concentrated in the peel, it was observed that the boiling was the best method for anthocyanin retention (43.7% loss of total anthocyanins), followed by frying (60.3% loss), grilling (84.4% loss) and baking (91.2% loss). The results of this study could be interpreted into the effect of thermal treatment on the functionality of EP anthocyanins.

In another study by Horincar, Enachi, Barbu, et al. (2020), as an alternative to chemically synthetic food additives, encapsulated EPE was employed to produce value-added pastry cream. The main limiting factor for the utilization of anthocyanins in food products is the stability of these compounds, which could be affected by enzymatic activity, temperature, oxygen, pH, metal ions and exposure to light or UV. Therefore, encapsulation could decrease the degradation rate and control the release of anthocyanins, as well as many other bioactive compounds (Karimi et al., 2020). In the mentioned study, EPE was encapsulated in WPI and acacia gum through freeze-drying, which resulted in microcapsules with an encapsulation efficiency of 94.31%, rich phenolic content and high antioxidant activity. Furthermore, pastry creams with 10% added encapsulated EPE presented an increase of TPC by 983.25% and total flavonoid content by 141.01%; also, the antioxidant potential was rather stable during a 72 h storage period. Total monomeric anthocyanin content, which was not detectable before, was measured at 0.225 mg of delphinidin-3-glucoside equivalents/g dry weight. All samples exhibited gel-like rheological behavior and regarding the textural properties, the addition of encapsulated EPE reduced the firmness of the sample, but did not affect other textural parameters. Sensory evaluation showed that compared to control samples, the overall acceptance and color scores of the enriched samples was improved. This study concluded that the encapsulated EPE could be used as a natural additive for the production of pastry cream, as well as other value-added foods such as chocolate, ice cream, jelly and candy products.

Other studies aimed to encapsulate EPE as a natural source of color and antioxidants. Sarabandi et al. (2019) used gum Arabic and maltodextrin as carriers for encapsulation of EPE through spray drying. They found out that maltodextrin is a better carrier for this purpose, since the production yield and solubility of the maltodextrin powders were higher, compared to the formulations with gum Arabic or the combination of both. The maltodextrin-encapsulated EPE also presented higher TPC and antioxidant activity. The size of the produced microcapsules in this study ranged between 50 and 70 μm, with maltodextrin particles being the smallest. Furthermore, they used maltodextrin-encapsulated EPE for the fortification of gummy candy. Results from sensory evaluation indicated that the addition of 1.5% of encapsulated EPE to gummy candy samples improved the color and overall acceptability score of the samples. Chatterjee and Bhattacharjee (2015) utilized an encapsulator in order to produce calcium alginate beads as a carrier for the encapsulation of EPE. After optimization through response surface methodology, optimal samples showed irregularly spherical beads, with an average diameter of 800 μm and an encapsulation efficiency of 73.48%. They found out that the shelf life of encapsulated EPE was 1500% higher, compared to non-encapsulated EPE. Furthermore, they employed their product as a coloring agent for jelly crystals, which resulted in crystals with significant red shade, compared to the color-blank sample. It was observed that the degree of redness was significantly higher in the samples treated with non-encapsulated EPE; however, the crystals treated with encapsulated EPE showed much more resemblance to the natural color of EP. In another study conducted by Condurache et al. (2019), EPE was encapsulated in 4 different mixtures of carboxymethylcellulose, pectin and bioactive peptides through freeze-drying. Bioactive peptides are resulted from the enzymatic hydrolysis of whey proteins and possess health-promoting benefits such as antimicrobial, antihypertensive and immunomodulatory activities. The encapsulation efficiency of the freeze-dried powders was calculated in the range of 69–77%. It was found out that the powders with the highest content of carboxymethylcellulose displayed a higher percentage of encapsulated EPE, which could be related to the improvement of wall material strength as a result of carboxymethylcellulose addition. All of the samples presented satisfactory antioxidant activity and after 28 days of storage, the powders with the highest content of pectin demonstrated better antioxidant activity. Results from release study in simulated gastrointestinal medium showed that in all of the samples, the release of encapsulated EPE was low during the gastric phase, but significantly increased during the intestinal phase. In both phases, the sample with the highest content of pectin was the most effective, with 4.28 ± 0.01% release in the gastric medium and 41.47 ± 1.40% release in the intestinal medium. These results point to the significant bioaccessibility improvement of the encapsulated EPE. This study also pointed out that the encapsulated EPE samples were not cytotoxic toward mouse fibroblast cell cultures, and even two of the samples significantly improved the viability of the treated cells. The overall results of this study demonstrated the successful enhancement of anthocyanin's bioavailability and controlled release. They also pointed out the benefits of using bioactive peptides as shell material. Another related study to bioactive peptides and EPE was conducted by Condurache et al. (2020). In this study, lactoferrin hydrolysate which was obtained from enzymatic hydrolysis and ultrafiltration of bovine lactoferrin, was bound to anthocyanins extracted from EP. Results of this study clarified the mechanisms of interactions between EPE anthocyanins and lactoferrin peptides and provided insights for formulating food products and ingredients with improved bioactive-binding properties.

6.2. Pectin

As summarized in the previous sections, EB is an excellent agricultural by-product for extraction of pectin and the pectin from this source illustrates very good functional properties. However, given the novelty of this subject, to the best of our knowledge, extracted pectin from EB has not been employed in any food, pharmaceutic or other products just yet. Nonetheless, there are countless potentials for utilization of this compound and several studies have already discussed this subject thoroughly (Christiaens et al., 2016; Mellinas et al., 2020; Wusigale et al., 2020). EBP is categorized as HMP, which is widely used as gelling and thickening agent in the food industry. HMP is capable of forming gels in an environment with high sugar concentration and acidic pH, which makes this substance ideal for utilization in foods with similar conditions, such as jams, jellies and marmalades (Christiaens et al.,. 2016). Furthermore, HMP is capable of forming thin films under the aforementioned conditions, which makes this compound useful for production of antioxidant, antimicrobial, preservative and pH indicator films (Kumar et al., 2020; Mellinas et al., 2020). EPP could be especially advantageous in this subject, because of its substantial TPC and antioxidant potential and could also be ideal for production of nutritionally valuable food products. EPP also illustrates good emulsifying properties and could be employed for production and stabilization of various types of emulsions (Gong et al., 2020). Recent trends regarding the utilization of pectin have focused on the application of pectin and its derivatives in pharmaceutical science and medicine, either as an independent medicinal substance (Beukema et al., 2020; Zaitseva et al., 2020) or for the development of drug delivery systems such as hydrogels (Amirian et al., 2021), as well as liposomes (Lopes et al., 2021) and other various types of nanoparticles (Zhao et al., 2020). The mentioned studies are just a small portion of the discussion of pectin utilization, and given to desirable characteristics of EBP, it is most likely going to fit well within this field in the near future.

6.3. Pullulan

Research in the subject of pullulan production from EB is still at its early stages and up until now, to the best of our knowledge, acquired pullulan from EB has not been employed in any researches, products, or industries. However, based on the aforementioned information regarding this product, it seems beneficial to address the shortage of research attempts in this regard. Several review studies have attentively addressed various aspects of pullulan application (Singh et al., 2019; Tiwari et al., 2019). Other than usual uses in food products as a thickening, gelling and stabilizing agent, in the past few years, many studies utilized pullulan in different aspects of food and pharmaceutical industries, especially in the fields of hydrogel and film production, along with fiber fabrication through electrospinning. The stair-step type structure and excellent mechanical properties of pullulan molecules enable this substance to offer an incredible film and fiber-forming properties (Celebioglu & Uyar, 2021). Recently, pullulan, usually in combinations with other polymers, has been utilized for preparation of films and coating for various purposes, such as fruit preservation (Pobiega et al., 2020), food packaging (Luís et al., 2020), edible films (Kowalczyk et al., 2020) and drug delivery (Shah et al., 2020). Moreover, hydrogel fabrication from pullulan, sometimes in combination with other polymers, has been another popular trend in the past few years (Zhang, Sun, Zhang, et al., 2020). Furthermore, the particular structure, as well as high water solubility and special rheological properties, makes pullulan an ideal substance for production of uniform and flawless micro and nanofibers by electrospinning. Guerrini et al. (2021) evaluated the effect of different solvents and solvent binary mixtures on the structural characteristics of curcumin-loaded pullulan nanofibers. They studied the effect of certain factors such as viscosity, interactions between solvent and polymer and solvent vapor pressure, as well as the effect of curcumin on size and morphology of produced nanofibers. Results from this research illustrate that employing DMF:DMSO with the ratio of 7:3 yields defect-free nanofibers with a mean diameter of 203 ± 32 nm and curcumin encapsulation efficiency of ∼96.5%. Pullulan has also been used as a copolymer with various polymers in the field of electrospinning. It is reported that by modifying the solution characteristics such as surface tension, viscosity and electrical conductivity, pullulan could enhance the electrospinnability of some problematic polymers (Qin et al., 2020). All of the mentioned applications, as well as numerous other studies that their explanation is beyond the scope of this review, highlights the importance of pullulan among current research trends and emphasizes the necessity of industrialized and convenient production of this substance from cheap and available materials, such as EB.

6.4. Industrial application feasibility

All of the mentioned studies regarding the valorization and application of EB were carried out in small-scale research laboratories. However, in order to truly address the conundrum of generation and accumulation of agricultural by-products, the scale of the related research studies must be upgraded to industrial proportions. This might not be an easy goal to achieve, since it is costly, time consuming and requires an intense level of cooperation among scientific communities, policy makers, and manufacturing and business sectors; Nevertheless, it seems absolutely necessary and could actually provide numerous, long term environmental and economic benefits and opportunities (Kazemi et al., 2019c).

To the best of the authors' knowledge, no large-scale industrial plant or facility for valorization of EB have been developed yet. However, the promising potentials of EB bioactives could guarantee the feasibility of such facilities. For instance, canning and ready-meal factories with high eggplant usage generate a considerable amount of EB every day. These factories could develop a valorization section along with their main production line, in which they acquire high value bioactives from their EB. This approach could significantly reduce the factory's waste generation and landfilling costs. Furthermore, they could use the acquired bioactives for fortification and improvement of their own products or sell them for profit. Another approach for valorization of EB is the development of independent valorization facilities near or inside the food processing industrial zones. This method is especially beneficial if the industrial zone is located near the eggplant cultivation fields or in a region with high consumption of eggplant products and could reduce costs and generate revenue for the business owners and provide jobs for the local community.

7. Conclusion and future prospects

Eggplant peel and calyx, the main by-products of eggplant fruit, are mostly generated by industrial food processing sections. These by-products are inexpensive, readily available for utilization and have the potential to yield substantial amounts of anthocyanins and pectin. EB anthocyanins, which are mostly consisted of delphinidin glycosides, offer superb health-promoting benefits such as antioxidant, antimicrobial and anticancer activities. EB pectin also illustrates great functional properties such as high levels of WHC and OHC, very good emulsifying and foaming properties and significant levels of antioxidant activity. Both of these bioactive compounds have been separately extracted from EB by employing the conventional SLE technique, as well as more efficient emerging methods such as UAE and MAE. Furthermore, by employing an integrated valorization technique, it is possible and advantageous to simultaneously extract anthocyanins and pectin from EB and then, as an approach to zero-waste valorization, utilize the leftovers as a potential carbon source for the production of pullulan through fermentation. Given the substantial economic and environmental advantages, it seems necessary for integrated valorization techniques of agricultural by-products to be further studied. Moreover, EB anthocyanins (in the form of EPE) have been successfully employed for fortification of several model foods as an alternative to artificial preservatives. However, further research is needed in regards to the application and health-promoting effects of bioactive compounds from EB, especially in the case of pectin and pullulan. Ultimately, it could be concluded that EB are excellent sources of bioactive compounds, valorization is the most beneficial approach to deal with these by-products and the acquired bioactive compounds have great functional and health-promoting properties and could be significantly useful in food and pharmaceutical industries.

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