By-products of plant food processing as a source of functional compounds — recent developments

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Introduction

Fruit juices and derived products such as nectars and drinks have experienced growing popularity within the last years. Grapes and apples are the most important fruits in the temperate zone, while oranges, pineapples, bananas, watermelons and mangos are the predominant fruits of tropical and subtropical areas. Among other reasons, the rise in consumption and export of processed fruit juices, pulps and concentrates may be attributed to better transportation and distribution systems, and improved cultivation and processing methods (Askar, 1998). Per capita consumption of juice is highest in Germany, accounting to more than 40 l in 1999 (Horenburg, 2001).

Fruits from the temperate zone are usually characterized by a large edible portion and moderate amounts of waste material such as peels, seeds and stones. In contrast, considerably higher ratios of by-products arise from tropical and subtropical fruit processing. Due to increasing production, disposal represents a growing problem since the plant material is usually prone to microbial spoilage, thus limiting further exploitation. On the other hand, costs of drying, storage and shipment of by-products are economically limiting factors. Therefore, agro-industrial waste is often utilized as feed or as fertilizer. However, demand for feed may be varying and dependent on agricultural yields. The problem of disposing by-products is further aggravated by legal restrictions. Thus, efficient, inexpensive and environmentally sound utilization of these materials is becoming more important especially since profitability and jobs may suffer (Lowe & Buckmaster, 1995).

Epidemiological studies have pointed out that consumption of fruits and vegetables imparts health benefits, e.g. reduced risk of coronary heart disease and stroke, as well as certain types of cancer. Apart from dietary fiber, these health benefits are mainly attributed to organic micronutrients such as carotenoids, polyphenolics, tocopherols, vitamin C, and others. Therefore, a minimum of five servings a day of vegetables and fruits, especially of green and yellow vegetables and citrus fruits, is recommended (Heimendinger & Chapelsky, 1996). Although consumers are increasingly aware of diet related health problems (Gilbert, 1997), a large group of the population lacks a generous intake of fruits and vegetables. Thus, dietary supplements and food fortification may be an alternative route to the
consumption of minor plant components that may have health benefits. Since synthetic additives are more and more rejected by consumers, functional ingredients should preferably originate from natural sources. This is particularly valid for phenolic compounds which, in contrast to most carotenoids and vitamins, are not chemically synthesized and need to be extracted from plant material.

The preparation of dietary fiber from by-products has already been summarized (Larrauri, 1999), and residual sources of natural antioxidants were the subject of a recent review (Moure et al., 2001). Therefore, the objective of this review is to highlight the potential of selected by-products of food processing as a source of natural food additives and ingredients with particular reference to investigations on the characterization of low-molecular components.

By-products of fruit processing

Apple

The highly variable composition of apple (Malus sp., Rosaceae) pomace and possible strategies of utilization have recently been reviewed (Kennedy et al., 1999a). According to the authors, the ongoing effort indicates that the ideal use has not yet been found. Production of pectin is considered the most reasonable way of utilizing apple pomace both from an economical and from an ecological point of view (Endreß, 2000; Fox, Asmussen, Fischer, & Endreß, 1991). In comparison to citrus pectins, apple pectins are characterized by superior gelling properties. However, the slightly brown hue of apple pectins caused by enzymatic browning may lead to limitations with respect to their use in very light-coloured foods. Approaches at bleaching apple pomace by alkaline peroxyde treatment resulted in the loss of the polyphenols and in pectin degradation (Renard, Rohou, Hubert, della Valle, Thibault, & Savina, 1997).

Apple pomace has been shown to be a good source of polyphenols which are predominantly localized in the peels and are extracted into the juice to a minor extent. Major compounds isolated and identified include catechins, hydroxyecinnamates, phloretin glycosides, quercetin glycosides, and procyanidins (Foo & Lu, 1999; Lommen, Godejohann, Venema, Hollman, & Spraul, 2000; Lu & Foo, 1997, 1998; Schieber, Keller, & Carle, 2001). Since some phenolic constituents have been demonstrated to exhibit strong antioxidant activity in vitro (Lu & Foo, 2000), commercial exploitation of apple pomace for the recovery of these compounds seems promising. Inhibitory effects of apple polyphenols and related compounds on cariogenicity of streptococci suggest their possible application in dentifrices (Yanagiwa, Kanda, Tanabe, Matsudaïra, & Oliveira Cordeiro, 2000).

Enhanced release of phenolics by enzymatic liquefaction with pectinases and cellulases represents an alternative approach at utilizing apple pomace (Will, Bauckhage, & Dietrich, 2000), but does not allow the recovery of pectin. Increasing efforts to improve juice yields by enzymatic liquefaction might even lead to shortages of apple pomace as a raw material. Furthermore, the use of cellulolytic enzymes for fruit juice production is still restricted by law. Recently, a method for the combined recovery of pectin and polyphenols from apple pomace was established (Carle et al., 2001). Gelling properties of colour-improved pectin were not affected. Thus, removal especially of oxidized polyphenols provides refined pectin qualities with extended fields of application. In addition, phenolic compounds may be obtained in good yields since the clean-up procedure can easily be integrated in the technical pectin production.

Grape

Apart from oranges, grapes (Vitis sp., Vitaceae) are the world’s largest fruit crop with more than 60 million tons produced annually. About 80% of the total crop is used in wine making (Mazza & Miniati, 1993), and pomace represents approximately 20% of the weight of grapes processed. From these data it can be calculated that grape pomace amounts to more than 9 million tons per year. Five to seven million tons are reported by other authors (Meyer, Jepsen, & Sørensen, 1998). Its composition varies considerably, depending on grape variety and technology of wine making.

A great range of products such as ethanol, tartrates, citric acid, grape seed oil, hydrocolloids, and dietary fiber are recovered from grape pomace (Bravo & Saura-Caliixo, 1998; Girdhar & Satyanarayana, 2000; Hong, 1988; Igartuburu, Pando, Rodriguez Luis, & Gil-Serrano, 1997; Nurgel & Canbas, 1998; Valiente, Arrigoni, Esteban, & Amado, 1995). Anthocyanins, catechins, flavonol glycosides, phenolic acids and alcohols and stilbenes are the principal phenolic constituents of grape pomace. Anthocyanins have been considered the most valuable components, and methods for their extraction have been reported (Mazza, 1995; Mazza & Miniati, 1993). In Chardonnay grape pomace, 17 polyphenolic constituents were identified by NMR spectroscopy (Lu & Foo, 1999). Chardonnay pomace was also a source of two unusual dimeric flavanols (Foo, Lu, & Wong, 1998). Catechin, epicatechin, epicatechin gallate and epigallocatechin were the major constitutive units of grape skin tannins (Souquet, Cheynier, Brossaud, & Moutouzet, 1996). A new class of compounds, amyloethylythio-flavan-3-ol conjugates, have been obtained from grape pomace by thiolysis of polymeric proanthocyanidins in the presence of cysteamine (Torres & Bobet, 2001).

Since grape and red wine phenolics have been demonstrated to inhibit the oxidation of human low-density lipoproteins (Frankel, Waterhouse, & Teissedre,
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1995; Teissedre, Frankel, Waterhouse, Peleg, & German, 1996), a large number of investigations on the recovery of phenolic compounds from grape pomace has been initiated. From a nutritional point of view, these phenolics are highly valuable since they are absorbed to a large extent (Martin-Carron, Garcia-Alonso, Goni, & Saura-Calixto, 1997). According to Shrikhande (2000) who recently reviewed health-promoting wine by-products, patent disclosures and research studies evolving from the ‘French Paradox’ observations (Renaud & De Lorgeril, 1992) have been instrumental in establishing a wine by-product phenol industry.

The antioxidant activity of grape pomace (Larrauri, Ruperez, & Saura-Calixto, 1996) has led to the development of a new concept of antioxidant dietary fiber (Saura-Calixto, 1998). Drying of pomace at high temperatures, however, may cause a significant reduction of extractable polyphenols and may also affect antioxidant properties (Bocco, Cuvelier, Richard, & Berset, 1998). Both in vitro and in vivo studies have recently demonstrated health-protecting effects of certain citrus flavonoids (Kuo, 1996; Manthey, Grohmann, & Guthrie, 2001; Tanaka et al., 1997). These findings may enhance their fields of application, thus making their recovery more profitable.

Citrus fruits

Due to the large amounts being processed into juice, a considerable by-product industry has evolved to utilize the residual peels, membranes, seeds, and other compounds. For a review, we refer to Braddock (1995) and literature cited therein. Residues of citrus juice production are a source of dried pulp and molasses, fiber-pectin, cold-pressed oils, essences, d-limonene, juice pulps and pulp wash, ethanol, seed oil, pectin, limonoids and flavonoids (Askar, & Treptow, 1998; Braddock, 1995; Ozaki, Miyake, Inaba, Ayano, Ifuku, & Hasegawa, 2000; Siliha, El-Sahy, Sulieman, Carle, & El-Badawy, 2000). Fiber-pectins may easily be recovered from lime peels and are characterized by high fiber contents (Askar & Treptow, 1998; Siliha et al., 1995). The main flavonoids found in citrus species are hesperidin, narirutin, naringin and eriocitrin (Mouly, Arzouyan, Gaydou, & Estienne, 1994). Peel and other solid residues of lemon waste mainly contained hesperidin and eriocitrin, while the latter was predominant in liquid residues (Coll, Coll, Laencine, & Tomas-Barberan, 1998). Citrus seeds and peels were found to possess high antioxidant activity (Bocco, Cuvelier, Richard, & Berset, 1998). Both in vitro and in vivo studies have recently demonstrated health-protecting effects of certain citrus flavonoids (Kuo, 1996; Manthey, Grohmann, & Guthrie, 2001; Tanaka et al., 1997). These findings may enhance their fields of application, thus making their recovery more profitable.

Mango

Mango (Mangifera indica L., Anacardiaceae) is one of the most important tropical fruits (Ramteke,
Mango seed kernel fat is a promising source of edible oil and has attracted attention since its fatty acid and triglyceride profile is similar to that of cocoa butter. Therefore, legislation has recently allowed mango seed kernel fat to be used as a cocoa butter equivalent. Mango seed kernels may also be used as a source of natural antioxidants. The antioxidant principles were characterized as phenolic compounds and phospholipids (Puravankara, Boghra, & Sharma, 2000). The phenolics were assumed to be mainly gallic and ellagic acids, and gallates. In another study, gallotannins and condensed tannin-related polyphenols were reported in mango seed kernels (Arogbha, 2000). Ethanolic extracts of mango seed kernels displayed a broad antimicrobial spectrum and were more effective against Gram-positive than against Gram-negative bacteria. Their active component was shown to be a polyphenolic-type structure, however, its exact nature still remains to be elucidated (Kabuki, Nakajima, Arai, Ueda, Kuwabara, & Dosako, 2000).

A standardized method for the recovery of good quality mango peel pectin with a degree of esterification of about 75% has recently been developed (Sudhakar & Maini, 2000). Mango peels were also reported to be a good source of dietary fiber containing high amounts of about 75% has recently been developed (Sudhakar & Maini, 2000). Mango seed kernels displayed a broad antimicrobial spectrum and were more effective against Gram-positive than against Gram-negative bacteria. Their active component was shown to be a polyphenolic-type structure, however, its exact nature still remains to be elucidated (Kabuki, Nakajima, Arai, Ueda, Kuwabara, & Dosako, 2000).

Banana

Banana (Musa × paradisiaca L., Musaceae) represents one of the most important fruit crops, with a global annual production of more than 50 million tons. Worldwide production of cooking bananas (plantains) amounts to nearly 30 million tons per year (Franke, 1997). Peels constitute up to 30% of the ripe fruit. About 1000 banana plants are estimated to yield 20–25 tons of pseudostems providing about 5% edible starch (Anand & Maini, 1997). Attempts at utilization of banana waste include the biotechnological production of protein (Chung & Meyers, 1979), ethanol (Tewari, Marwaha, & Rupal, 1986), α-amylase (Krishna & Chandrasekaran, 1996), hemicellulases (Medeiros, 2000) and cellulases (Krishna, 1999). Very recently, anthocyanin pigments in banana bracts were evaluated for their potential application as natural food colorants. It was concluded that the bracts proved to be a good and abundant source of anthocyanins of attractive appearance, as well as being a useful tool in anthocyanin identification since all six most common anthocyanidins (delphinidin, cyanidin, pelargonidin, peonidin, petunidin and malvidin) are present (Pazmino-Duran, Giusti, Wrolstad, & Durst, 2001). Most of the carotenoids found in banana peels were demonstrated to be xanthophylls esterified with myristate, and to a lesser extent with laurate, palmitate or caprate (Subagio, Morita, & Sawada, 1996).

Guava

Guava (Psidium guajava L., Myrtaceae) is a rich source of relatively low methoxylated pectins (50%), amounting to more than 10% of the dry weight (Muroki & Saint-Hilaire, 1977). Since wastes constitute only 10–15% of the fruit, the use of guava for pectin production is limited (Askar & Tretpow, 1998). The seeds, usually discarded during processing of juice and pulp, contain about 5–13% oil rich in essential fatty acids.
Papaya

Papain, a proteolytic enzyme used as a meat tenderizer and as a stabilizing agent in the brewing industry, is recovered from the latex of papaya fruit (Carica papaya L., Caricaceae). Furthermore, papaya fruits may also be used for the production of pectin. Owing to their spicy flavour which is caused by glucosinolate degradation, the seeds are sometimes used as a substitute and even as an adulterant for pepper. The seed oil is low in polyunsaturated fatty acids, but defatted papaya seed meal contains high amounts of crude protein (40%) and crude fiber (50%) (Jagtiani, Chan, & Sakai, 1988).

Passion fruit

The waste resulting from passion fruit (Passiflora edulis SIMS, Passifloraceae) processing consists of more than 75% of the raw material. The rind constitutes 90% of the waste and is a source of pectin (20% of the dry weight). Passion fruit seed oil is rich in linoleic acid (65%) (Askar & Treptow, 1998).

Kiwi

Kiwi (Actinidia chinensis PLANCH., Actinidiaceae) waste results from rejected kiwifruits which comprise up to 30% of the total kiwifruit crop, and from kiwifruit pomace after juice production. A comprehensive review of the components and potential uses of kiwifruit waste has recently been given (Kennedy et al., 1999b), inferring that only little work has so far been conducted on finding uses for kiwifruit pomace. The total dietary fiber content of kiwifruit pomace amounts to approximately 25% on a dry weight basis (Martin-Cabrejas, Esteban, Lopez-Andreu, Waldron, & Selvendran, 1995). Phenolic acids, flavanol monomers, dimers and oligomers, and flavonol glycosides have recently been characterized in kiwifruit pulp (Dawes & Keene, 1999).

By-products of vegetable and potato processing

Tomato

Tomato (Lycopersicon esculentum MILL., Solanaceae) juice is the most important vegetable juice with respect to per capita consumption, followed by carrot juice. About 3–7% of the raw material is lost as waste during tomato juice pressing (Otto & Sulc, 2001). Tomato pomace consists of the dried and crushed skins and seeds of the fruit (Avelino, Avelino, Roseiro, & Collaco, 1997). The seeds account for approximately 10% of the fruit and 60% of the total waste, respectively, and are a source of protein (35%) and fat (25%).

Tomato seed oil has attracted interest since it is rich in unsaturated fatty acids, especially in linoleic acid (Askar & Treptow, 1998; Roy, Goto, & Hirose, 1996). Recently, the optimization of degumming, bleaching and steam deodorization was reported (Bhullar & Sogi, 2000). Sensory evaluation of products made with tomato seed and sunflower oil revealed no significant differences (Sogi, Kiran, & Bawa, 1999).

Lycopene is the principal carotenoid causing the characteristic red hue of tomatoes. Most of the lycopene is associated with the water-insoluble fraction and the skin (Sharma & Maguer, 1996). Therefore, skin extracts are especially rich in lycopene. Baysal, Ersus, and Starmans (2000) clearly stated that a large quantity of carotenoids is lost as waste in tomato processing. Supercritical CO2 extraction of lycopene and β-carotene from tomato paste waste resulted in recoveries of up to 50% when ethanol was added (Baysal et al., 2000). Enzymatic treatment of tomato marc enhanced lycopene extractability (Böhm, Tiemeni, & Otto, 2000). Recently, saccharification to obtain biomass from tomato pomace has also been reported (Avelino et al., 1997). Haddadin, Abu-Resh, Haddadin, and Robinson (2001) described the utilization of tomato pomace as a substrate for the production of vitamin B12.

Carrot

Carrot (Daucus carota L., Apiaceae) juices and blends thereof are among the most popular non-alcoholic beverages. From 1995 to 1999, German carrot juice production increased by 69%, now amounting to more than 42 million liter. Steady increase of carrot juice consumption has also been reported from other countries (Chen & Tang, 1998). Despite considerable improvements in processing techniques including the use of depolymerizing enzymes, mash heating, and decanter technology, a major part of valuable compounds such as carotenes, uronic acids, and neutral sugars is still retained in the pomace which is usually disposed as feed or as fertilizer. Juice yield is reported to be only 60–70%, and up to 80% of carotene may be lost with the pomace (Sims, Balaban, & Matthews, 1993). According to our own investigations, total carotene content of pomace may be up to 2 g per kg dry matter, depending on processing conditions (Stoll, Schieber, & Carle, 2001).

Various attempts were made at utilizing carrot pomace in food such as bread (Ohsawa, Chinen, Takanami, Kuribayashi, & Kurokouchi, 1994), cake, dressing and pickles (Ohsawa et al., 1995), and for the production of functional drinks (Henn & Kunz, 1996). However, consumer acceptance of such products still needs to be demonstrated, especially since sensory quality may be adversely affected (Henn & Kunz, 1996). Pigments of spray-dried carrot pulp waste proved to be prone to degradation during storage, depending on
storage time and temperature. It was suggested that the stability of carotenoid powder can be greatly enhanced by employing appropriate packaging methods and storage conditions (Chen & Tang, 1998). Freeze-dried powder showed a higher pigment stability during storage than the spray-dried product (Tang & Chen, 2000). Significant isomerization which can also contribute to decolorization was not observed after 15 weeks of storage of \( \beta \)-carotene encapsulated in a maltodextrin matrix (Desobry, Netto, & Labuza, 1997).

Smokers were officially recommended to refrain from foods fortified with \( \beta \)-carotene (BgVV, 1998). According to a recent recommendation, daily intake of isolated \( \beta \)-carotene should not exceed 2 mg (BgVV, 2001). Therefore, carrot pomace represents a valuable natural source of \( \alpha \)- and \( \beta \)-carotene which may be recovered and applied as functional food ingredients in their genuine proportion.

Onion

The amount of onion (Allium cepa L., Alliaceae) waste produced annually in the European Union is estimated at approximately 450,000 tons. The major by-products resulting from industrial peeling of onion bulbs are brown skin, the outer two fleshy leaves and the top and bottom bulbs. Owing to their strong characteristic aroma and their susceptibility to phytopathogens, onion wastes are not suitable as fodder. However, they are a source of flavour compounds and fiber compounds and particularly rich in quercetin glycosides (Hertog, Hollman, & Katan, 1992; Waldron, 2001). The major flavonoids of mature onion bulbs are quercetin 3,4'-O-diglucoside and quercetin 4'-O-monoglucoside, accounting for more than 85% of the total flavonoids (Price & Rhodes, 1997). Since quercetin from onions is rapidly absorbed and slowly eliminated, it could contribute significantly to antioxidant defense (Hollman et al., 1997). An overall processing scheme for exploiting onion waste has been given by Waldron (2001).

The effects of pressure-cooking, divalent cations and extrusion-cooking on cell-wall polymers of onion waste have been investigated in detail (Lecain, Ng, Parker, Smith, & Waldron, 1999; Ng, Lecain, Parker, Smith, & Waldron, 1999; Ng, Parker, Smith, & Waldron, 1999). With respect to the recovery of fructans and fructooligosaccharides, the outer two fleshy leaves have been demonstrated to be the most suitable sources (Jaime et al., 2000). The production of alcohol and snacks from onion pomace has also been reported (Horiuchi, Yamauchi, Osugi, Kanno, Kobayashi, & Kuriyama, 2000; Kee, Ryu, & Park, 2000, 2001).

Olive

The by-products resulting from olive oil extraction are the vegetation water, also called black water or vegetable water, and the olive husk including skins and stones. Depending on the processing conditions, 50–110 kg of water result from 100 kg of olives (Vitolo, Petarea, & Bresci, 1999). The husk can be reprocessed for the recovery of olive oil, or extracted with an organic solvent to yield husk oil. Dried husk is utilized as fuel or animal feed (Gasparrini, 1999). A process for the separation of the vegetation water from the solids by evaporation has been recently described. The remaining solid fraction representing 98% of the organic load could be mixed with the husk and used as a fuel (Vitolo et al., 1999). Olive oil waste waters are rich in antioxidant compounds, particularly in hydroxytyrosol derivatives (Visioli et al., 1999). Hydroxytyrosol strongly inhibited LDL oxidation stimulated by 2,2'-azobis(2-aminopropane) hydrochloride (Aruoma et al., 1998). Further investigations point out that hydroxytyrosol and oleuropein are potent scavengers of superoxide radicals (Visioli, Bellomo, & Galli, 1998). Tyrosol and hydroxytyrosol are dose-dependently absorbed by humans and eliminated as their glucuronide conjugates, indicating a good bioavailability (Visioli et al., 2000, Galli et al., 2000). An environmentally friendly synthesis of hydroxytyrosol using mushroom tyrosinase as a biocatalyst has recently been established and might facilitate further metabolic studies (Espin, Soler-Rivas, Cantos, Tomas-Barberan, & Wichers, 2001).

Red beet

More than 200,000 tons of red beet (Beta vulgaris L. ssp. vulgaris, Chenopodiaceae) are produced in Western Europe annually, most of which (90%) is consumed as vegetable. The remainder is processed into juice, coloring foodstuff and food colorant, the latter commonly known as beetroot red (Henry, 1996). Though still rich in betalains, the pomace from the juice industry accounting for 15–30% of the raw material (Otto & Sulp, 2001) is disposed as feed or manure. The coloured portion of the beetroot ranges from 0.4 to 2.0% of the dry matter, depending on intraspecific variability, edaphic factors and postharvest treatments (Stintzing, Schieber, & Carle, 2000). Beets are ranked among the 10 most potent vegetables with respect to antioxidant capacity ascribed to a total phenolic content of 50–60 \( \mu \)mol/g dry weight (Cao, Sofic, & Prior, 1996; Kähkönen et al., 1999; Vinson, Hao, Su, & Zubik, 1998). A more recent investigation showed that total phenolics decreased in the order peel (50%), crown (37%) and flesh (13%). Epidermal and subepidermal tissues, i.e. the peel, also carried the main portion of betalains with up to 54%, being lower in crown (32%) and flesh (14%) (Kujala, Loponen, Kika, & Pihlaja, 2000). Whereas the coloured fraction consisted of betacyanins and betaxanthins, the phenolic portion of the peel showed l-tryptophane, p-coumaric and ferulic acids, as well as cyclodopa glucoside derivatives (Kujala, Loponen, & Pihlaja, 2001). Therefore, the exploitation of peel and
pomace for phenolics and betalains is a real need. Temperature- and pH-dependent in vitro antiradical activities have been reported for betanin and betanidin carrying phenolic hydroxy groups (Escribano, Pedreno, García-Carmona, & Munoz, 1998; Pedreno & Escribano, 2001), thus being more efficient than the betaxanthins vulgaxanthin I and II (Escribano et al., 1998). However, betaxanthins that bear phenolic structures in their amino acid moiety, e.g. portulacaxanthin II, miraxanthin III, miraxanthin V and dopaxanthin (Stintzing et al., 2001), may act in a similar way. Little is known about the in vivo absorption of betalains. In a recent study with betalains from a cactus fruit, a degradation rate of 24–29% was shown to occur in the stomach, of 20–26% in the small intestine, and of 26–29% in the large intestine (Reynoso, Giner, & de Meijia, 1999). Betacyanins were demonstrated to be strong antioxidants in various model systems, and their positive charge may increase their affinity to biological membranes which are the preferred targets of oxidation (Kanner, Harel, & Granit, 2001). Literature data imply a low rate of betalain absorption, and a critical concentration for the bioactivity of these compounds in human plasma has yet to be established. Toxicological studies revealed that betanin, the major compound from red beet, did not exert allergic potential (Pourrat, et al., 1995). However, methods for the complete separation of steroidal alkaloids from phenolic compounds prior to their use in foodstuff would be desirable to avoid any risk for human health (Rodriguez-Saona, Giusti, & Wrolstad, 1998; Rodriguez-Saona, Wrolstad, & Pereira, 1999). Chemistry, biochemistry, and dietary role of potato polyphenols have been recently reviewed by Friedman (1997).

**By-products of sugar production**

Since the world sugar market is currently suffering from very high stocks and low prices, long-term options for the utilization of by-products are urgently required (Anonymous, 2000). Sugar cane (Saccharum officinarum L., Poaceae) and sugar beet (Beta vulgaris L. ssp. vulgaris var. altissima DÖLL, Chenopodiaceae) are the most important crops for the production of sugar. Molasses represents the runoff syrup from the final stage of crystallization. It mainly consists of fermentable carbohydrates (sucrose, glucose, fructose), and of non-sugar compounds which were not precipitated during juice purification. Furthermore, molasses contains substances formed chemically or enzymatically during processing and storage (betaine and other amino acids, Maillard products, Strecker decomposition products, lactic acid, mineral and trace elements, and vitamins especially of the B-group). Molasses is used as feed and as a source of carbon in fermentation processes, e.g. for the production of alcohol, citric acid, t-lysine and t-glutamic acid (Higginbotham & McCarthy, 1998).

In volume, bagasse is the by-product of highest relevance. The fibrous residue from the extraction process is utilized as fuel and as a source of pentosans, for the production of furfural from pentosan-rich raw material, and for the recovery of fibrous products (Delavier, 1998). Granulated activated carbon (GAC) produced from sugar cane bagasse showed some potential as a sugar decolorizer (Ahmedna, Marshall, & Rao, 2000a) but was inferior to GAC produced from pecan shells (Ahmedna et al., 2000b).

Depending on the process, exhausted beet pulp has a dry matter content of 8–15%. Therefore, its economic utilization requires dewatering which is mostly performed by mechanical pressing (pressed pulp), followed by thermal drying. Pressed pulp is an energy-rich animal feed the shelf-life of which can be extended by ensiling (Harland, 1998; Heller, 1998). Enzymatic release of ferulic acid from sugar beet pulp and subsequent bioconversion to vanillin in a two-step process has been
Concluding remarks

Far from claiming completeness, this review discusses the potential of the most important by-products of plant food processing as a source of valuable compounds. The relevance of this topic is illustrated by a number of related reviews that were published during the past 5 years (Anand & Maini, 1997; Das, 2001; Kennedy et al., 1999a,b; Larrauri, 1999; McKee & Latner, 2000; Moure et al., 2001; Shrikhande, 2000; Sudhakar & Maini, 1995). For cereal and legume by-products and spent grains from brewing, which are mainly sources of dietary fiber, we refer to the recent treatise of McKee and Latner (2000). Antioxidants from cereals and legumes, among others, have also been considered by Moure et al. (2001). Particular attention to bioactive compounds of cereals has been given by Andlauer and Fürst (1998, 1999). Studies on the utilization of Brassicaceae such as cauliflower (Brassica oleracea L.) (Femenia, Robertson, Waldron, & Selvendran, 1998), of spent soluble coffee waste (Regalado et al., 2000) and tea leaves (Zandi & Gordon, 1999) are rather limited and deserve further attention. By-products and the compounds recovered thereof may be broadly classified into insoluble (fibers etc.), water-soluble (e.g. phenolics) and lipid-soluble (e.g. carotenoids) compounds. In the present review, a product-related categorization has been given preference since this has been considered more useful to the reader.

Future trends

The exploitation of by-products of fruit and vegetable processing as a source of functional compounds and their application in food is a promising field which requires interdisciplinary research of food technologists, food chemists, nutritionists and toxicologists. In the near future, we are challenged to respond to the following research needs: First, food processing technology should be optimized in order to minimize the amounts of waste arising. Second, methods for complete utilization of by-products resulting from food processing on a large scale and at affordable levels should be developed. Active participation of the food and allied industries with respect to sustainable production and waste management is required. Third, natural and anthropogenic toxins such as solanin, patulin, ochratoxin, dioxins and polycyclic aromatic hydrocarbons need to be excluded by efficient quality control systems. Minimization of potentially hazardous constituents, e.g. solanin, amygdalin, and optimization of valuable compounds such as carotenoids and betalains may also be achieved by plant breeding. Fourth, there is a need for specific analytical methods for the characterization and quantification of organic micronutrients and other functional compounds. Fifth, the bioactivity, bioavailability and toxicology of phytochemicals need to be carefully assessed by in vitro and in vivo studies. This is possibly of greatest importance since the results of the ATBC study (ATBC Study Group, 1994) and the CARET trial (Omenn et al., 1996) surprisingly suggest that high dosages of β-carotene achieved by formulations with high bioavailability might lead to harmful effects. Also, in the case of phenolics, Parr and Bolwell (2000) concluded that it still remains to be clarified whether certain individual phenolics are particularly active, or whether the consumption of a broad spectrum of phenolics is important. Under certain conditions, e.g. in the presence of some transition metal ions, antioxidants such as phenolics may behave as prooxidants (Fukumoto & Mazza, 2000). Finally, Dillard and German (2000) pointed out that the ‘activity’ of many phytochemicals has only been tested in in vitro models, and this may bear no relationship to the situation in vivo.

Undoubtedly, functional foods represent an important, innovative and rapidly growing part of the overall food market. However, their design, i.e. their complex matrix and their composition of bioactive principles, requires careful assessment of potential risks which might arise from isolated compounds recovered from by-products. Furthermore, investigations on stability and interactions of phytochemicals with other food ingredients during processing and storage need to be initiated. Since functional foods are on the boundary between foods and drugs, their regulation still proves difficult. In any case, consumer protection must have priority over economic interests, and health claims need to be substantiated by standardized, scientifically sound and reliable studies.

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