Chapter

Valorization Options of Strawberry Extrudate Agro-Waste. A Review

Juan Cubero-Cardoso, Antonio Serrano, Ángeles Trujillo-Reyes, Denys K. Villa-Gómez, Rafael Borja and Fernando G. Fermoso

Abstract

This review summarizes and critically analyzes the different types of potential valorization options for strawberry extrudate in order to have a broader overview of the potential management of this waste. Animal feed is commonly used as a management option for the strawberry extrudate; however, most of the strawberry extrudate is disposed in landfills. Strawberry extrudate contains different bioactive compounds that encourage the use of an alternative management approach than landfilled. The present review offers a complete comparative, including the advantages and drawbacks of each reviewed technique, to facilitate the selection of the most suitable technology for the different valorization scenarios. This review has been structured in three sections: 1. Composition of the strawberry extrudate and strawberry especially focused on their content in bioactive compounds. 2. The different techniques of extraction and purification of bioactive compounds. 3. The handling and management of the resulting biomass after the extraction process of bioactive compounds.

Keywords: strawberry extrudate, bioactive compounds, bioproducts, extraction techniques, purification

1. Introduction

In 2016, 8 million tons of strawberry were produced in the world with a value of agricultural gross production of 17,739 million US$ [1]. Besides its market as fresh product, strawberry is also used to produce many types of by-products, due to its peculiar flavor and aroma. Strawberry by-products are mainly formulated from a strawberry concentrate. The most common technology to obtain the strawberry concentrate is by extrusion. Strawberries are extruded by twin-screws up to several sieves with different mesh sizes. The sieves retain a residual fraction formed by the fibrous part and the achenes, named strawberry extrudate, which accounts about 7% of the manufactured strawberry [2].

Animal feed is commonly used as a management option for the strawberry extrudate, however, most of the strawberry extrudate is disposed in landfills, contributing to greenhouse emissions due to its high organic load [3]. Alternatives for strawberry extrudate management are required to avoid severe environmental impacts that cause landfills, such as negative effects on agricultural soil quality, polluting of aquatic ecosystems and atmospheric contamination [4].

Similar to strawberry, strawberry extrudate contains substances of high interest such as bioactive compounds. Some of these bioactive compounds have beneficial health effects on cardiovascular, neurological or cancerous disorders [5]. Due to their health benefits, bioactive compounds have an economic interest for different commercial sectors, such as the pharmaceutical, food and chemical industries [6]. Added to bioactive compounds, strawberry extrudate could be used to obtain other types of resources such as bioenergy [7, 8]. It is also well known the high phenolic composition in the achenes and in the pulp of the strawberry [9].

A general biorefinery scheme as a management option for the strawberry extrudate should look for synergies between unitary processes of extraction of bioactive compounds, purification and the management of the final biomass of the strawberry extrudate after extraction (**Figure 1**).

The extraction of bioactive compounds in agro-waste materials, such as the strawberry extrudate can be performed through various extraction techniques [10]. The main objective at this step consists of solubilizing the compounds of interest, with less possible impurities and making it an economically profitable technique. Extraction techniques in literature can be clustered into two groups: conventional extraction techniques, e.g. hydrothermal treatments, which are widely used at lab and full scale [11], and in recent years, more innovative techniques, e.g. enzyme assisted extraction. Additionally, combined extraction techniques between conventional and innovative techniques are being carried out to achieve high extraction yield [12]. All these extraction techniques will be revised and analyzed in the present chapter.

Any of these extraction techniques usually generate a liquid phase, with the bioactive compounds of interest, and a solid phase with a high amount of organic matter. After purification process of the liquid phase, a new liquid phase remains without the extracted bioactive compounds. Therefore, just the recovery of compounds of interest from the strawberry extrudate does not solve the problem of stabilization of the biomass of the strawberry extrudate and the use of a subsequent

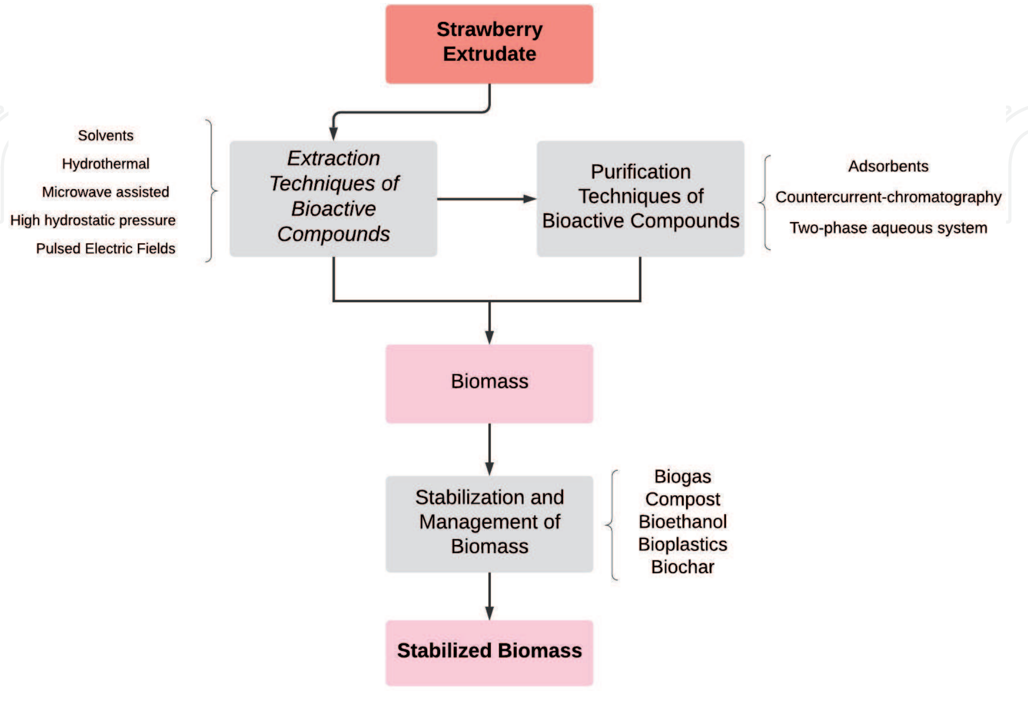

Figure 1.
General scheme of a biorefinery approach as a valorisation option for strawberry extrudate.

treatment is necessary for its stabilization [13]. The liquid phase after purification and the solid phase must undergo a new treatment for stabilization. In addition, extraction and purification processes consume energy which should be valued. The main options for assessing and stabilizing biomass after the extraction and purification process of the bioactive compounds should be focused on obtaining bioenergy and other bioproducts of interest [14].

The present chapter aims to summarize the bioactive compounds present in strawberries, to summarizes and critically analyzes the different extraction and purification techniques for the recovery of these bioactive compounds, as well as the different options for the management and stabilization of the strawberry extrudate after the extraction process.

2. Bioactive compounds in strawberry extrudate and strawberries

2.1 Nutrients

Strawberry extrudate presents similar nutrients composition than strawberry [15]. The strawberry has high concentration of dietary fibrous (2 g fibrous/100 g raw strawberry), such as lignin, hemicellulose, cellulose, and pectin, containing small amounts of protein (0.4–0.5 g protein/100 g raw strawberry) and fat (0.1 g fat/100 g raw strawberry) [16, 17].

The strawberry contains high concentrations of vitamin C, contributing to 24% to the antioxidant capacity of strawberries [16]. The recommended daily intake of vitamins (100–150 mg/day) can be satisfied with an average of 100 g of strawberries per day [18]. Furthermore, strawberry is a source of many other vitamins in smaller amounts, such as vitamin E, vitamin A, vitamin B6, vitamin K, thiamine, riboflavin, folate acid, and niacin (0.01–0.4 g vitamin/100 g raw strawberry) [5, 19]. Strawberry is also rich in manganese, potassium, and a good source of iodine, magnesium, copper, iron, and phosphorus [5, 16].

The sugar composition of strawberries varies with the degree of maturity of the fruit [20], being glucose, fructose, and sucrose the main sugars in strawberries [5]. Sugars in strawberries are involved in the taste of the fruit and are responsible for the caloric value of the strawberries. Organic fatty acids such as citric acid, malic acid, succinic acid, tartaric acid, oxalic acid, and fumaric acid are ones of the response of the taste, texture, pH, and color of the strawberry, and can alter the sensory quality of this fruit [6].

2.2 Phytochemicals

Figure 2 shows a general scheme for the classification of phytochemical compounds that can be founded in the strawberry extrudate. Phytochemicals are widely studied, mainly due to the extensive types of compounds that have potential biological benefits in humans. The main phytochemicals in strawberries are the flavonoids, followed by the hydrolysable tannins and the phenolic acids and, as minor constituents, the condensed tannins [5].

2.2.1 Flavonoids

Flavonoids are divided into two groups, i.e. anthocyanins, and anthoxanthines. Anthoxanthines, in turn, are grouped into five subclasses, i.e. flavones, flavonols, flavanones, flavanols, and isoflavones [21]. The three main classes of flavonoids in strawberries are anthocyanis, flavonols, and flavanols [22].

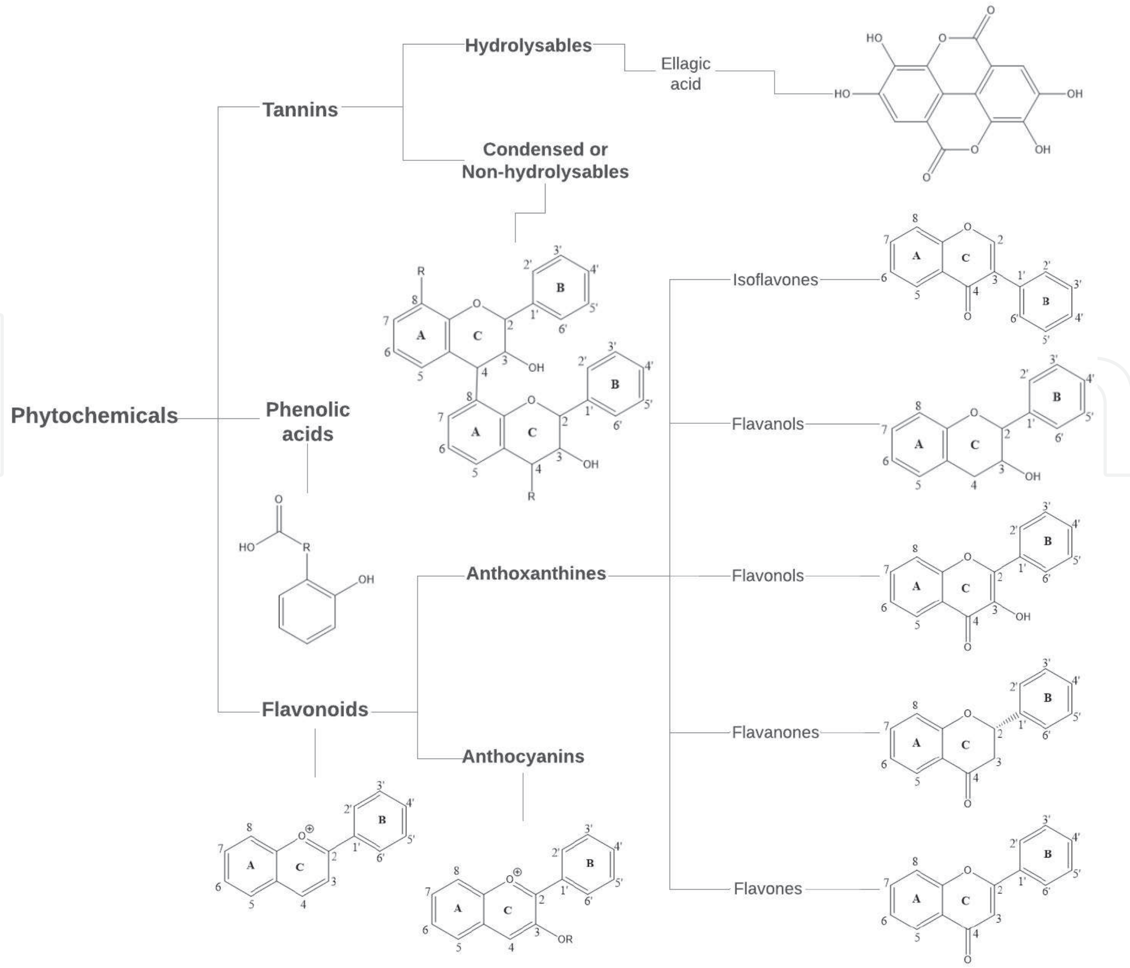

Figure 2.
General scheme of phytochemicals contained in strawberries.

The most relevant flavonoids present in strawberries are the anthocyanins due to their high concentration, approximately 20–47 mg/100 g raw strawberry [16]. More than 25 different pigments of anthocyanins have been described in the different varieties of strawberries [5]. Anthocyanins are responsible for the red color in strawberries [16]. The most important anthocyanins of the strawberry belong to the family of pelargonidin aglycones and cyanidin aglycones [23–25]. According to several studies, pelargonidin-3-glucoside is the dominant anthocyanin in strawberries [16, 24, 26–28]. The interest in anthocyanins have recently increased because of its pharmacological and therapeutic properties [5]. Anthocyanins have shown to positive effect toward reduction of coronary diseases, anticancer, antitumor, anti-inflammatory and anti-diabetic effects; as well as improving visual acuity and cognitive behavior [29]. These therapeutic effects of anthocyanins are connected to their high antioxidant activity [29]. In addition, anthocyanins can be used as a pigment in the food industry [29].

The second most important group of flavonoids in strawberries are flavonols, with approximately 1.5–3.4 mg/100 g raw strawberry [5, 16, 30, 31]. The most important flavonols of the strawberry belong to the family of quercetin and kaempferol, being the quercetin-derivatives the most abundant flavonols in strawberries [5, 17, 25–27]. Quercetin, in particular, is a potent antioxidant, cytoprotective, and anti-inflammatory [30].

Finally, the third group of flavonoids in strawberries are flavanols. Flavanols are the only class of flavonoids that do not naturally occur as glycosides. They are found in strawberries as monomeric compounds, such as catechins, and in polymeric form, which are called condensed or non-hydrolysable tannins [5, 25]. These compounds can be difficult to measure in the strawberry because they are usually presented as part of a complex mixture of phenolic substances. Because of this, the amount of catechins present is sometimes overestimated [31]. At low concentrations flavanols particularly the catechins, are used as sweetening and/or flavoring additives. These flavonols improve taste and sweetness but are not substitutes for sweeteners and flavorings as they do not have taste and are a little astringent. Some authors have pointed out that their role is to make the receptors in the mouth more sensitive to sweeteners, thus lowering the levels of the sweeteners and flavorings used [21, 32].

2.2.2 Tannins

Tannins are classified into two groups: non-hydrolysable or condensed tannins and hydrolysable tannins (**Figure 2**). The condensed tannins are also called proanthocyanins, and are bound to the flavanols [33]. The content of condensed tannins in strawberries is approximately 54–163 mg/100 g raw strawberry [16]. In strawberries, the most relevant condensed tannins are procyanidins from catechin and its polymers. Condensed tannins are commonly found in the pulp of strawberries and achenes [5]. Due to the variety of physiological activities, they have been reported to possess, directly and indirectly, antioxidant, antimicrobial, anti-allergic and antihypertensive properties, as well as to inhibit the activities of some enzymes and physiological receptors [34].

The most common hydrolysable tannins in strawberries are ellagitannins, specifically sanguiin H-6 and ellagic acid [5, 26–28]. The content of ellagitannins in strawberries is approximately 10–23 mg/100 g raw strawberry [16]. Ellagic acid is an ellagitannin present in the secondary metabolism of vegetables, its main characteristic is its antioxidant, antimicrobial, antimutagenic, anticarcinogenic and antiviral capacity [16]. The content of ellagic acid in strawberries is approximately 1–2 mg/100 g raw strawberry [16]. Due to the phenolic nature of ellagic acid, this compound tends to react by forming complexes with other molecules of proteins, alkaloids, and polysaccharides, so that it is usually found as ellagitannins esterified with glucose, because of this it is difficult to find it free [20]. The properties of ellagic acid are also exploited in the food industry, so it is used in the manufacture of nutraceutical drinks and food supplements. Likewise, the application of ellagic acid for food preservation is of great impact for the perishable food industry, using its antioxidant activity for microorganisms inhibition [35].

2.2.3 Phenolic acids

Strawberries contain a variety a of phenolic acids which are presented as derivatives of the hydroxycinnamic acid, such as caffeic acid, and hydroxybenzoic acids such as gallic acid [5]. The content of phenolic acids in strawberries is approximately 0.8–6.7 mg/100 g raw strawberry [16]. The major hydroxycinnamic acid in strawberries is p-coumaroylhexose, but ferulic acid and caffeic acid glycosides have also been identified in strawberries [26, 27]. Hydroxycinnamic acid derivatives are responsible for the bitter taste of the strawberry, and it is used in the manufacture of creams [33, 36]. The primary derivative of hydroxybenzoic acid is p-hydroxybenzoic glycoside [28]. The p-hydroxybenzoic glycoside is widely used in the synthesis of organic compounds and their esters, known as parabens, which are used as preservatives in cosmetics [37].

3. Extraction and purification of bioactive compounds in strawberry extrudate

3.1 Extraction techniques

3.1.1 Solvents extraction

The extraction with solvents is a technique to isolate a substance from a solid or liquid mixture. This technique is currently used in combination with other techniques such as microwaves and ultrasound since the solvent only extracts soluble compound. Due to the strawberry extrudate nature, the solid–liquid extraction can be carried out with a Soxhlet extractor, which is one of the most commonly used conventional extraction techniques [38]. The extraction efficiency depends mainly on the choice of solvents [39]. The polar character of the bioactive compounds allows their solubility in various solvents, such as water, alcohols, and acetone [40].

Recently, numerous studies have explored the extraction of bioactive compounds using deep eutectic solvents from various groups of natural sources [41]. The formation of eutectic solvents is the result of the complexation of a halide salt, which acts as a hydrogen bond receptor, and a hydrogen bond donor [41]. Some eutectic solvents have been developed from the combination of primary metabolites and bio-renewable starting materials, e.g., sugars, alcohols, amino acids and organic acids [41]. Eutectic solvents produce less adverse effects on the environment, allowing to replace conventional chemical methods [41].

There is a long variety of studies on solvent extraction focusing on the extraction of bioactive compounds. An evaluation of the effect of different solvents and acids in the extraction of anthocyanins from strawberry fruits concluded that acetone provided an efficient and reproducible extraction, avoiding problems with pectins and allowing the concentration of the sample at low temperature [42]. In another study, it was observed that the acetone/acetic acid mixture (99:1, v/v) reached good results for the qualitative and quantitative evaluation of polyphenols present in strawberries [43].

3.1.2 Hydrothermal extraction

Hydrothermal extraction is a process in which the matter is treated by adding hot water or water vapor [38]. Steam explosion is another kind of hydrothermal treatment where the matter is treated with saturated water vapor at high pressure followed by rapid depressurization [44]. The disadvantage of using hydrothermal treatments is that they affect thermosensitive compounds and might form undesirable compounds [45].

Hydrothermal extraction at low temperature, i.e. ranging between 50 and 90°C, mainly induces the de-flocculation of macromolecules [46]. Hydrothermal extraction at medium temperature, i.e. ranging between 150 and 180°C, solubilizes cellulosic and hemicellulose biomass [47]. The steam explosion treatment, with temperature ranging between 180 and 260°C and increase in pressure of 0.69–4.83 MPa, it is able to solubilize lignocellulose biomass [44].

Several studies confirm the successful extraction of bioactive compounds by these hydrothermal extractions [48, 49]. Extraction of bioactive compounds in strawberry extrudate has been studied by applying hydrothermal treatments in the range of 90–200°C, [15]. Thermal treatment at 150°C for 60 minutes was the most efficient process based on the solubilization of sugars and phenols as well as the antioxidant capacity of the liquid phase produced [15].

3.1.3 Microwave assisted extraction

Microwaves are electromagnetic fields in a frequency range of 300 MHz to 30 GHz, which are generally operated at a frequency of 2.45 GHz [10]. Microwaves can access biological matrices and interact with polar molecules, such as water, which vibrate or rotate by the effect of microwaves and generate heat and can enhance the processes of extraction of bioactive compounds [10, 50]. Microwave assisted extraction has been successfully applied in anthocyanin extraction processes in grape skins [51], the recovery of pectins from press residues of various berries, i.e. red and black currant, raspberry and elderberry [52] and to extract phenolic antioxidants from peanut skins [53].

3.1.4 High hydrostatic pressure extraction

High hydrostatic pressure extraction is a method that works at high pressures ranging from 100 to 1000 MPa. These high pressures cause cell deformation, cell membrane damage, protein denaturation, deprotonation of charged groups, and the breakdown of bonds, making bioactive compounds more accessible for extraction [54]. High hydrostatic pressure extraction is considered to be a faster and more efficient technique than other conventional extraction methods [55, 56]. In addition, high hydrostatic pressure extraction has the advantage of not increasing the temperature during the processing time, so it would be an ideal method to extract thermosensitive compounds.

Several high hydrostatic pressure extraction studies have been carried out with strawberries for the extraction of bioactive compounds. The impact of high hydrostatic pressure extraction on total strawberry puree phenols was observed by Patras et al., [56], which reported that the amount of total phenols increases as the pressure in high hydrostatic pressure extraction increases [56]. In another study, the change in kaempferol, and quercetin quantity in strawberries pulps were tested at different pressures and for different processing times [57]. According to this study, the change in the amount of kaempferol was not very significant and the amount of quercetin increased with increasing pressure [57]. Another study showed that the nutritional and sensory qualities of strawberry puree after high-pressure processing at 500 MPa and 50°C for 15 min were much better than after a heat treatment at 90°C for 15 min [58].

3.1.5 Pulsed electric fields extraction

Pulsed electric fields or high intensity pulsed electric fields consist of a short time electrical treatment, between nanoseconds to milliseconds, in which the material located between two electrodes is exposed to a strong electric pulse of intensity field of 100 to 300 V/cm Pulsed Electric Fields or 20 to 80 kV/cm high intensity pulsed electric field, the operation parameters being the duration and number of pulses [59, 60]. Pulsed electric fields can produce the electrical rupture of the cell membranes producing the formation of pores, what is known as electroporation [60, 61]. Pore formation improves cell permeability allowing the recovery of bioactive compounds [62]. Compared to other non-thermal treatments such as the high hydrostatic pressure extraction method, pulsed electric field extraction methods require a much shorter processing time, higher extraction efficiency and these techniques can be easily applied in continuous operation [59]. Therefore, pulsed electric fields is a promising technique for different applications in the food industry because they can improve extraction capacity and recovery of nutritionally valuable compounds as well as the bioavailability of micronutrients and compounds in a wide range of foods [59].

Several studies on the extraction of antioxidant compounds in agri-foods show enhanced yields with pulsed electric fields. For instance, a comparison study between a heat treatment at 90°C for 60 or 30 seconds and high intensity pulsed electric field in strawberries juice, showed that strawberry juice treated with high intensity pulsed electric field maintained greater amount of phenolic acids and total anthocyanins than thermally treated juices [63, 64]. Likewise, the recovery of phenols from the shell of the pomegranate by pulsed electric field has been assayed, resulting in a similar antioxidant extraction yields and an energy saving of 50% compared to an ultrasound extraction technique [65].

3.1.6 Extraction techniques comparison

After reviewing the different extraction techniques that have been applied to the strawberry and strawberry extrudate, a summary describing their most interesting aspects is shown in **Table 1**. The aspects that have been compared are: the specificity of the extraction techniques with the bioactive compounds, the possibility of combining with other extraction techniques, the ability to release bioactive compounds, the potential degradation of bioactive compounds, possibility of intracellular attack, bonds breakage and whether the technique has a high operational and investment cost. The choice of the best technique for the strawberry extrudate is a tailor-made solution for each situation that will depend of the investment capacity, target compounds to be recovered or the required extraction yield.

3.2 Purification techniques of bioactive compounds

3.2.1 Adsorbents

There are many studies that show the properties of adsorbents to separate, concentrate and purify various compounds [66, 67]. Functionality, porosity, irregularities, surface area, tightly bonded impurities, internal porous structure, particle size, ionic strength, pH, and temperature all influence physical adsorption [66]. The temperature influences the adsorption in two ways, increasing the transport

Extraction technique	Specificity	Possibility of combination	Ability to release compounds	Degradation of bioactive compounds	Intracellular attack	Breaks of bonds	High cost
Solvents extraction	x	x					
Hydrothermal extraction		x	x	x		x	
Microwave assisted extraction		x	x	x	x	x	
High hydrostatic pressure extraction		x	x	x	x	x	x
Pulsed electric fields extraction		x	x	x	x	x	

Table 1.
Summary table of characteristics for comparing extraction techniques.

speed through the outer boundary layer and inside the pores due to the decrease in the viscosity of the solution, and changing the capacity of the adsorbent. However, high temperatures can promote irreversible interactions [67]. Another important parameter for purification with adsorbents is pH. For example, at acid pH, the adsorption of phenolic compounds by different adsorbents increases because the phenols are not dissociated and dispersion interactions predominate [66]. At alkaline pH, the adsorption decreases due to the dissociation of hydroxyl groups and carboxyl groups [66]. There are many types of adsorbents such as activated carbons, mineral adsorbents, synthetic polymeric adsorbents, ion exchange resins, lignin and lignocellulosic materials, adsorbents based on polysaccharides and others [66]. Among the available adsorbents Amberlite XAD adsorbents are widely used in the concentration of polyphenols [68]. Zhang et al. [69] reported the isolation and structural characterization of 10 phenolic compounds from strawberry extracts using a combination of Amberlite XAD-16 and C18 columns, HPLC-UV, and nuclear magnetic resonance spectroscopy methods.

3.2.2 Countercurrent-chromatography

Countercurrent chromatography is a technique widely used in the purification of natural products [70]. Countercurrent chromatography is a liquid–liquid partition chromatography process in which both the mobile phase and the stationary phase are liquid [70]. The main advantage of countercurrent chromatography, when compared to equivalent techniques such as low pressure liquid chromatography, is that there are no adsorption losses in the stationary phase [70]. The range of selectivity offered by chromatographic resins is equivalent to the range of selectivity offered by the different solvent systems [70].

Several studies have shown the importance of countercurrent chromatography for the purification of bioactive compounds from strawberry. The compound 2,5-dimethyl-4-hydroxy-3[2H]-furanone 6′O-malonyl-β-d-glucopyranoside was isolated from a strawberry glycosidic extract (Fragaria × *ananassa*, cv. Senga Sengana) by countercurrent chromatography [71]. Peonidin-3-glucoside and malvidin-3-glucoside were obtained from grapes in a single step, while in a second step, cyanidin-3-glucoside was isolated [72]. In another research, the separation of anthocyanin monomers of high purity from mulberry fruits was developed [73].

3.2.3 Two-phase aqueous system

Two-phase aqueous system is a liquid–liquid fractionation technique that is usually formed by mixing two polymers in aqueous media, for example, polyethylene glycol and dextran or maltodextrin, or by a polymer and a salt, such as polyethylene glycol and salts of phosphates, citrates or sulphates [74–76]. This method has advantages over other purification techniques due to a comparatively low consumption of energy and time, as well as the possibility to be designed for a continuous operation. Moreover, two-phase aqueous systems are effective for many types of substances, especially for the concentration and purification of bioactive compounds [74, 75]. Several studies have demonstrated the suitability of this technique for the purification of bioactive compounds such as phenolic compounds from fig fruits (*Ficus carica* L.) [76], or the purification of gallic acid from natural matrices with ionic liquids [77]. Furthermore, two-phase aqueous system has been applied for the purification of polyphenols from a model solution of gallic acid and three real samples of red and white wine, and orange juice in combination with macro and micro extractors [78]. Polyphenols have been also extracted from *Aronia melanocarpa* berries, using ultrasound-assisted extraction in combination with the two-phase aqueous system [79].

4. Stabilization of biomass by obtaining bioenergy and bioproducts

4.1 Biogas production

Anaerobic digestion is a microbiological process, in absence of oxygen, where organic matter is progressively degraded by an heterogeneous bacterial population to methane (55–70%) and carbon dioxide (30–45%) [80]. Anaerobic digestion presents some fundamental advantages such as the possibility of working at high rates of organic load, and the produced methane can be used as an energy source due to its heating value (35,793 kJ/m^3, at 1 atm, 0°C), which equals to 1 kg of raw coal or 0.76 kg of standard coal [3, 11]. The use of biogas for energy supply reduces deforestation, soil erosion and environmental pollution [81, 82]. Also, it can improve the energy efficiency of various production processes due to the energetic contribution that provides [82]. In addition, a wet waste called digestate, which is a mixture of partially degraded organic matter, microbial biomass, and inorganic compounds, is produced during biomethanization and could be used as a base for fertilizers or organic amendments [82, 83].

Several studies on anaerobic digestion of strawberries extrudate have been carried out. The results of one these studies reveal that strawberries extrudates have a high level of anaerobic biodegradability (90% in VS, (total volatile solids)) and that a substantial amount of methane can be obtained in this way (312 mL CH_4 STP/g added VS) (STP: standard temperature and pressure conditions, i.e. 0°C, 1 atm) at an organic loading rate range of 2.04 to 3.51 kg VS/m^3·d [84]. In another study of anaerobic digestion of strawberry waste from supermarkets, using an organic loading rate of 0.55–4.4 (g/L·d), the experimental biogas and methane yields were 0.588 and 0.231 L/g, respectively [85]. It has been observed that sometimes it is necessary to co-digest strawberry extrudate with a substrate that provides alkalinity, such as sewage sludge [86, 87]. Co-digestion studies of strawberry extrudate with other substrates such as fish waste [3] and glycerol [83] have also been studied. Anaerobic digestion of strawberry extrudate is a promising technique but it should be further studied since low alkalinity of the extrudate together with formation of inhibitory compounds caused by the extraction process could negatively affect the digestion process.

4.2 Compost production

Composting has been proposed for a long time as a quite cheap option for agricultural waste management [2]. Composting has also been proposed as a post-treatment for the produced digestate after anaerobic digestion [88]. Composting is the bio-oxidative conversion of organic waste into an organic amendment. According to Gutiérrez et al. (2017) [2], the cost of composting varies in a wide range from $40 to $500 per throughput ton depending on the technology. Composting costs vary widely depending on the type of operation, which ranges from the most simple ones, such as opening windrows, to more complex procedures like in-vessel aerobic composting that allows smell emissions to be controlled and prevents environmental pollution [2]. The great disadvantage is that a considerable amount of offensive odors can be emitted during the process due to the generation of volatile organic compounds [89]. Other disadvantages are the long process time and the necessity of a proper monitoring [90]. Co-composting of a waste mixture containing strawberry extrudate, fish waste, sewage sludge and bulking agent has been successfully proven [2, 89].

4.3 Bioethanol production

Bioethanol is one of the most produced alcohols from the fermentation of sugars found in fruits and vegetables [7, 91–93]. Theoretically, any organic product with a high content of sugars and starch, such as strawberry extrudate, may be susceptible to obtaining bioethanol [91]. Inedible sources from the strawberry extrudate such as lignocellulosic biomass, which mainly comprises cellulose, hemicellulose, and lignin, can be hydrolysed to produce a mixture of pentoses and hexoses that can be transformed into bioethanol [94]. Bioethanol from agro-waste, such as strawberry extrudate, could be a promising technology that involves four processes, pre-treatment, enzymatic hydrolysis, fermentation and distillation, this final step is crucial for the process to be economically viable on a commercial scale due to high energy consumption in the form of steam to increase the yield of bioethanol production when lignocellulose materials are used as raw material [93]. These processes have several challenges and limitations, such as the efficient pre-treatment process to eliminate lignin from the lignocellulosic agro-residues. The proper pre-treatment process can increase the concentrations of fermentable sugars after enzymatic hydrolysis, thus improving the efficiency of the entire process [92].

4.4 Bioplastics production

Fossil fuel depletion, global warming, and problems of pollution of the environment that provoke plastics in its life cycle are encouraging the development of biodegradable plastics [95, 96]. Agri-food waste are usually rich in many useful substances such as lipids, polysaccharides, and aromatics, which could be used for the manufacture of biodegradable polymeric materials. Bioplastics already play an important role in the sectors of packaging, agriculture, consumer electronics and motoring, but still have a very low share in the total production of plastics. Currently, about 1% of the annual tons of plastic are bioplastics [97]. Examples of such bioplastics are exopolysaccharides, polycaprolactone, polybutylene succinate, polybutylene adipate terephthalate, polyhydroxyalkanoates or polyhydroxybutyrates [97, 98]. For obtaining bioplastics from agri-food waste, the waste must be treated to extract or isolate specific macromolecules, such as cellulose, lignin, suberin, starch, or monomers, such as vegetable oils, tannins and terpenes [96, 99]. A study conducted on the production of bioplastics from Murta fruit extract, that is a native Chilean berry, showed the feasibility of using berries for bioplastic production [8].

4.5 Biochar production

Biochar is the solid carbonaceous residue produced through organic waste and used as a soil improver [100, 101]. Biochar is produced through several types of methods such as pyrolysis, torrefaction or hydrothermal carbonization [100, 101].

There are no studies reported in the literature dealing with the production of biochar from strawberry extrudates. However, the above-mentioned techniques (pyrolysis, torrefaction and hydrothermal carbonization) could be potentially applied for this substrate. Several studies have been carried out on the hydrothermal carbonization of other agri-food waste, such as olive cuttings and olive pulp [102]; grape marc [103]; olive mill waste, canned artichoke and orange waste [104].

5. Conclusions

This chapter has reviewed up-to-date literature on the bioactive compounds contained in strawberries, which have an important health and market value. Different extraction and purification techniques to obtain valuable compounds from strawberry extrudate have been reviewed and analyzed. The reviewed techniques present different advantages and drawbacks that were analyzed to facilitate the selection of the most suitable process for each valorisation scenario. Finally, different stabilization options for the biomass remaining after extraction have also been reviewed. Stabilization is required to avoid severe environmental impacts, and additionally could be an economically beneficial aid for balancing the cost of the extraction of high value-added compounds. As usually for any waste management option, selection of the best extraction, purification and stabilization technique for the strawberry extruded is a tailor-made solution for each situation.

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Conflict of interest

The authors declare no conflict of interest.

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