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Chapter 6. Eco-efficient electrotechnologies to convert food waste and by-products to high added value food components

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Abstract

The food losses and waste are one of the major issues occurring throughout the food supply chain that has a negative impact on climate change and livelihoods. Hence, the modern food industries are constantly looking for sustainable strategies in order to avoid or valorise this food waste. In the present chapter, the emergent electrotechnologies, such as high voltage electrical treatments and electromembrane technologies will be discussed in terms of their use for converting food waste or by-products into high added value components. For each technology, the operation principles as well as conventional and novel applications in different food sectors (e.g. meat, dairy, plant, fish) will be considered. Eventually, the main technological issues as well as research and development perspectives will be highlighted.

Keywords: eco-efficiency, electroactivation, electrodialysis, food waste, high voltage electrical treatments

6.1 Introduction

The modern global food supply chains face serious challenges related to the constantly increasing population and demand for high-quality food. However, around 1/3 of the food produced in the world is lost or wasted (FAO, 2011) despite the fact that more than 800 million people suffer from hunger (HLPE, 2014). These food losses and waste lead to multiple issues such as significant environmental footprint related to production, transport and disposal of lost or wasted food as well as socio-economic issues related to food insecurity due to the low availability and high cost of high-quality food especially for the vulnerable populations. Moreover, the diverse socio-economic problems were even worsened by Covid-19 pandemic pushing the governments and food industries to focus on the rational use of produced food and avoidance of food losses and waste (Galanakis *et al.*, 2021). The above-mentioned issues are tackled by multiple Sustainable Development Goals (SDGs) established by the United Nations and especially SDG-2 (End Hunger) and SDG-12 (Ensure sustainable consumption and production patterns). Among diverse strategies of food losses and waste reduction covered

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by SDGs, the application of innovative and eco-efficient technologies to convert food losses and waste into high added value products is encouraged. The eco-efficiency concept is normalised by ISO 14045 and is defined as an aspect of sustainability that relates the environmental performance of a product system to its value (ISO, 2012). The environmental impact can be estimated using a life cycle assessment approach allowing a broad characterization of diverse impacts occurring throughout the life cycle of a product (energy and resource consumption, global warming potential, ecosystem quality, impacts on human health, etc.) (ISO, 2006). Regarding the value component of eco-efficiency, it can be estimated as a monetary value (e.g. production cost), a physical value (e.g. units or volume of production), a functional value (health benefits of the product) as well as an esthetical value (product appearance). In the present chapter, we will focus on emergent electrotechnologies, namely high voltage electrical treatments (HVET), electrodialysis (ED) and electroactivation (EA), allowing the eco-efficient conversion of food losses and waste to food components having high nutritional, functional and bioactive properties. We will consider the operational principles as well as the main applications of each technology to solve the food losses and waste issues.

6.2 High voltage electrical treatments

HVET consist of application of short pulses (ns-ms) of a high electric field strength (0.1-50 kV/cm) to the treated food matrix situated between two electrodes (Figure 6.1). There are two major types of HVET, namely pulsed electric field (PEF) and high voltage electrical discharge (ARC or electrical arc), which differ by the electrode configuration in the treatment chamber and phenomena occurring during treatment. PEF treatment occurs between two pane electrodes generating the mechanical stress, created by externally applied potential difference,

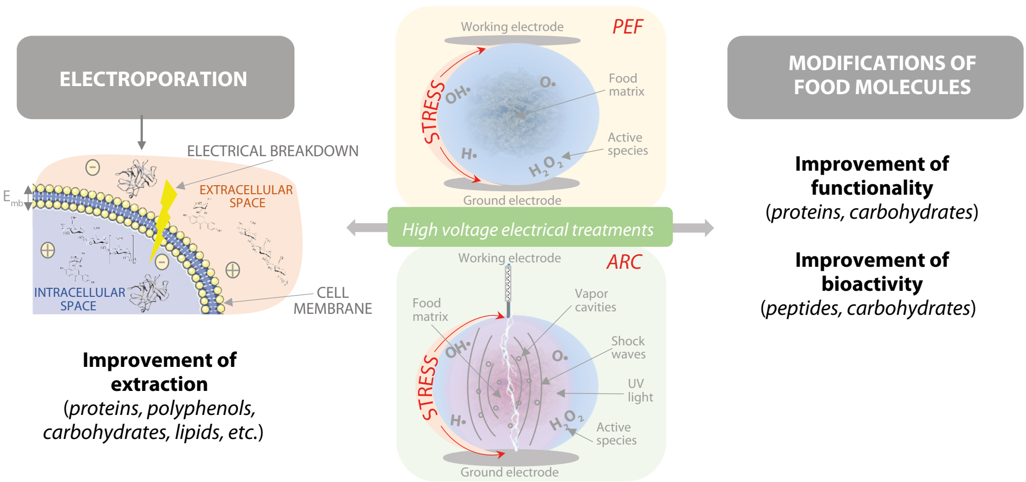

Figure 6.1. Principles and main applications of high voltage electrical treatments (pulsed electric field (PEF) and high voltage electrical discharge (ARC)) for food waste valorisation. E_{mb} refers to transmembrane potential.

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as well as multiple reactive species (radicals, ozone, hydrogen peroxide, etc.) (Boussetta *et al.*, 2013). In the case of ARC, mechanical stress is accompanied by generation of reactive species as well as physical phenomena, such as shock waves, UV light and cavitation bubbles (Boussetta *et al.*, 2013; Denat *et al.*, 2015).

The classical application of HVET (Figure 6.1) for valorisation of food by-products and waste refers to the electroporation phenomenon occurring when the applied potential difference is higher than the critical value of the transmembrane potential (E_{mb}≈0.2-1 V (Weaver and Chizmadzhev, 1996)). Electroporation can be reversible and irreversible mainly depending on applied electric field strength (Tylewicz, 2020). In the case of plant tissues (d≈30-60 µm), electroporation can be generated using quite moderate electric field strength (200-1000 V/cm) whereas for the smaller cells like easts and microalgae (d≈1-10 µm), the higher electric field strength (10-50 kV/cm) should be applied to achieve electroporation (Barba *et al.*, 2015a; Vorobiev and Lebovka, 2017). Thus, the main parameters to take into account for efficient cell electroporation are the following (Tylewicz, 2020):

- electric field strength;
- pulse duration;
- pulse number (frequency);
- pulse shape;
- cell size;
- cell geometry;
- proximity and interconnections of cells;
- treatment media conductivity.

Multiple studies have demonstrated significant benefits in mass transfer improvement and increase in extraction yield of diverse food molecules during HVET of a wide array of agro-food by-products and wastes. For instance, polyphenols, well-known health promoting compounds, can be effectively extracted from grape pomace, fruit and vegetable peels (Barba *et al.*, 2015a). Such extraction seems to be advantageous from an eco-efficiency point of view. Indeed, HVET does not apply the organic solvents and high temperatures, which can cause the degradation of polyphenols. In terms of energy consumption for extraction, HVET seems to be more advantageous compared to conventional treatments. The average energy consumption varies between 1 and 15 kJ/kg for HVET compared to 20-40 kJ/kg for mechanical treatment and >100 kJ/kg for heat and freezing/thawing treatments (Vorobiev and Lebovka, 2017). Other high-added value compounds (e.g. proteins, carbohydrates, lipids), which could be used as food additives, nutraceuticals and drugs, can be as well extracted from multiple agro-food by-products such as shrimp shells, animal bones, different leaves, peels, seeds, oil-cakes, spent grains, hulls and other residues (Barba *et al.*, 2015b; Mahnič-Kalamiza *et al.*, 2014; Poojary *et al.*, 2016; Vorobiev and Lebovka, 2017). Moreover, the efficiency of HVET treatment can be improved using a hybrid approach and combining them with pressing, moderate thermal treatments, green solvents and other emerging technologies.

While the application of HVET for the improvement of extraction of different food molecules from food waste is well known, the other aspect of HVET aiming at improvement of the

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functionality and bioactivity of food molecules is still emergent and poorly explored. The most part of studies focus on food proteins issued from by-products. For instance, the proteins from whey or soybeans were studied to explore the changes in their functionalities caused by HVET (Giteru *et al.*, 2018; Xiang, 2008). So far, the changes in solubility, viscoelastic and gelling properties were reported only for PEF treated proteins suggesting that such modifications can lead to the improvement of protein functionality prior to its incorporation to a certain food matrix. The modification of protein functionality can be explained by the changes of inter-/intramolecular interactions of protein molecules exposed to HVET. These changes are due to the partial loss of protein tertiary and secondary structures, the exposure of hydrophobic groups initially buried in the protein core as well as modifications in protein polarisation exhibited as an increase in peptide dipole moment (Giteru *et al.*, 2018). The very perspective application of above-mentioned modifications of protein molecules was reviewed by Dong *et al.* (2021) who proposed the use of HVET as a non-thermal method to address food allergy problems. Moreover, recent studies have demonstrated that HVET can substantially increase the production of peptides from proteins (Agoua *et al.*, 2020; Mikhaylin *et al.*, 2017). Indeed, Agoua *et al.* (2020) demonstrated that catalytic efficiency of HVET pretreated β-lactoglobulin was significantly higher compared to the native and preheated protein leading to a very remarkable improvement of eco-efficiency in peptide generation. Moreover, these authors demonstrated that peptides could be generated even without the use of enzymes increasing the attractiveness of HVET for industrial applications. Furthermore, the application of HVET to already derived peptides was reported to increase their bioactive potential, namely antioxidant and immunomodulatory activities (Zhang *et al.*, 2021). These applications demonstrate a very promising potential of HVET in order to eco-efficiently convert the low value food proteins to high value peptides having multiple bioactivities (e.g. ACE-inhibitory, opioid, antimicrobial, antioxidant, hypocholesterolemic, etc.), which can be used as natural food additives and nutraceuticals. The second class of food macromolecules treated by HVET in order to enhance their functionality is polysaccharides. For instance, the application of HVET to chitosan (polymer obtained by deacetylation of chitin isolated from crustacean shells) solutions allowed to reduce its molecular weight and promote antifungal, antibacterial and antitumor activities (Luo *et al.*, 2010). Other examples of the use of HVET to modify polysaccharides refer to starches. Indeed, HVET allow modification of polysaccharides' functional properties (e.g. swelling capacity, viscosity, solubility, pasting) due to the changes in their microstructure and conformation caused by applied electric field (Giteru *et al.*, 2018).

Though the use of HVET to convert food by-products, losses and waste in high added value products seems to be eco-efficient compared to conventional approaches, these treatments have several issues. Firstly, electrochemical reactions occurring on the electrode-electrolyte interfaces during the treatment can affect the quality of the final product (Pataro and Ferrari, 2020). Moreover, these reactions can provoke the electrode corrosion especially in the food matrices having low pH values and containing chloride ions. Other possible issue is the fouling formation leading to a distortion of local electric field, arcing and significant decrease of the HVET performance. Eventually, the HVET equipment design needs to be improved in order to satisfy the industrial requirements for the conventional and emergent applications of this technology for valorisation of diverse agri-food wastes and by-products (Pataro and Ferrari, 2020).

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6.3 Electrodialysis

Electrodialysis (ED) is an electromembrane process allowing the concentration, purification and separation of charged molecules as well alkalization and acidification of food matrices. In conventional ED (Figure 6.2A), the cell consists of two main components such as electrodes, to which the potential difference, playing the role of driving force, is applied, and ion-exchange membranes playing the role of selective barrier and allowing the migration of species having a particular charge (Strathmann, 2004). Ion-exchange membranes consist of a polymeric matrix containing fixed charged groups. Cation-exchange membranes have negatively charged fixed groups ($-SO_3^-$, $-COO^-$, $-PO_3^{2-}$, etc.) and are selectively permeable to cations, whereas anion-exchange membranes have positively charged groups ($-NR_3^+$, $-NHR_2^+$, $-PR_3^+$, etc.) and are selectively permeable to anions. This particular permselectivity allows demineralization or concentration of treated solutions.

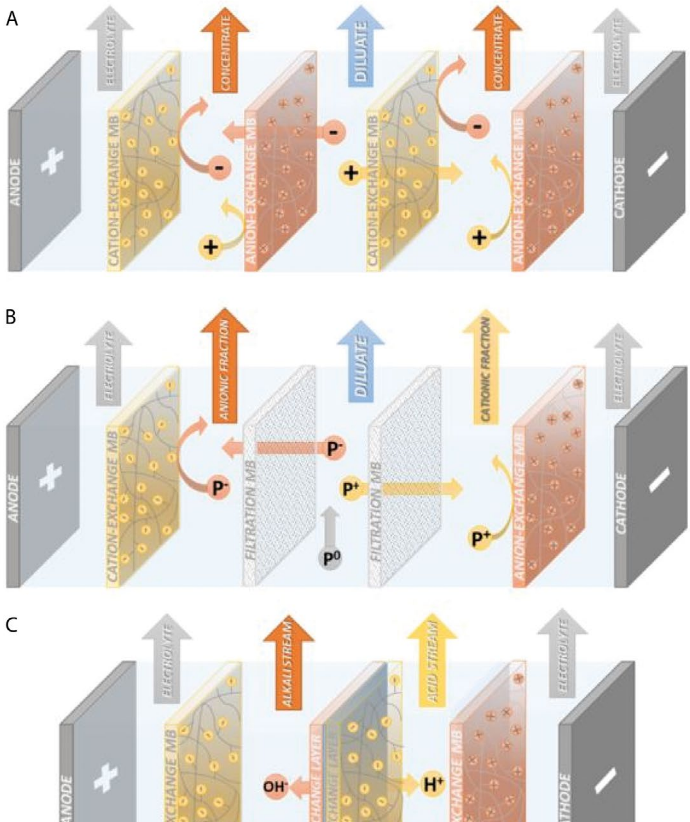

Figure 6.2. Principles of electrodialysis process; (A) conventional electrodialysis (ED); (B) electrodialysis with filtration membrane (EDFM); and (C) electrodialysis with bipolar membrane (EDBM).

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In terms of food waste treatment, conventional ED can be applied for demineralization of multiple wastewaters such as dairy and seafood processing wastewaters (Mikhaylin and Bazinet, 2016a). One of the most successful applications of ED in food sector is a demineralization of dairy whey (by-product of cheese, Greek yogurt and casein production) allowing its purification and subsequent use in different food formulations (infant food, sport nutrition, etc.). Additionally, ED can be applied to remove different ions from vinasses, seafood wastes, grape must and potato juice (Mikhaylin and Bazinet, 2016a). Furthermore, the concentration and recovery of different organic acids from wide array of fermentation broths obtained from food by-products and waste can be successfully carried out using ED (Bak *et al.*, 2019; Mikhaylin and Bazinet, 2016a). It is worth noting that ion-exchange membranes allow passage of relatively small charged species (mostly inorganic and organic salt ions). Therefore, the emergent variant of ED called electrodialysis with filtration membrane (EDFM) was recently developed to allow the separation of charged species having relatively high molecular weight (e.g. peptides, polyphenols) (Bazinet and Doyen, 2017).

The principle of EDMF is demonstrated in Figure 6.2B, where the peptide mixture containing positively and negatively charged as well as neutral peptides is treated. The result of EDMF is obtainment of three fractions, namely anionic fraction (containing negatively charged peptides), cationic fraction (containing positively charged peptides) and the final peptide mixture (containing mostly neutral peptides and charged peptides, which did not have enough time to migrate during EDMF treatment). Another possible configuration of EDFM stack can contain several filtration membranes having different molecular weight cut-off providing an additional selectivity based on the size of separated molecules. Thus, fractions containing peptides endowed with multiple bioactivities (antimicrobial, anticancer, antioxidant, antihypertensive, etc.) could be obtained by EDMF from different food by-products and waste, such as snow crab and fish by-products, flaxseed, whey proteins, animal blood and others (Bazinet and Firdaous, 2013; Henaux *et al.*, 2019; Przybylski *et al.*, 2021). The EDUF process seems to be more eco-efficient compared to conventionally used chromatographic techniques and pressure-driven membrane processes in order to obtain bioactive fractions from agro-food by-products. Indeed, this technology uses double charge/size selectivity, which cannot be attained in conventional filtration processes, and does not use any harmful solvents (the issue of chromatographic process). However, the scale-up of this technology should be investigated in order to estimate its viability and efficiency on an industrial scale.

The third major type of ED, which can be applied to convert agro-food waste and by-products to high added value products, uses a special type of membrane consisting of two layers of ion-exchange membranes with hydrophilic interface between them (Figure 6.2C). This special membrane type allows water dissociation when applying the potential difference to electrodes. Therefore, one can obtain two streams having acid and basic pH values. This technology is called electrodialysis with bipolar membrane (EDBM) and was successfully applied to recover proteins from plant and animal sources by precipitating them to their isoelectric point in the acid compartment (Mikhaylin and Bazinet, 2016a). For instance, soy protein isolate (95% purity) can be obtained from soy flakes (waste or by-product of soybean oil production) using EDBM with lower salt content and without use of chemical agents compared to conventional

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production (Bazinet *et al.*, 1998). Another example is the use of hybrid technology comprising EDBM and ultrafiltration to produce caseins and caseinates from skim milk (by-product of butter and cream production) (Mikhaylin *et al.*, 2018). This process was reported to be more environmentally friendly compared to acid/base processes conventionally used in the industry. Another example of the use of EDBM is the recovery of organic acids from by-products to use as food additives (Bailly, 2002).

Despite the wide range of application of different configurations of ED process, it has some limitations, mainly related to the membrane fouling and concentration polarization phenomena (Bazinet and Geoffroy, 2020; Mikhaylin and Bazinet, 2016b). Indeed, treatment of complex solutions containing colloidal particles, organic molecules, inorganic salts (mostly multivalent ions) and more rarely microorganisms can provoke different types of fouling (Mikhaylin and Bazinet, 2016b) leading to the drastic decrease of the process performance and necessitating the use of cleaning agents or replacement of membranes, which raise the overall cost of the ED treatment. The second major issue relates to concentration polarization, which is mostly important for the conventional ED. This polarisation occurs at the interfaces of the ion-exchange membranes due to the fact that ions are transferred more readily through the membranes than in solution, which creates a concentration gradient (Nikonenko *et al.*, 2014). This phenomenon hampers the ion transfer through the ion-exchange membranes when applying a certain current density (called limiting current density). Thus, in practice, the increase in membrane surface area (costly option) is preferred to increase in current density in order to attain a desirable ED performance. However, nowadays there are multiple approaches allowing to tackle the fouling and concentration polarization issues, such as the use of intensive current regimes, pulsed-electric or reverse current modes, membrane modification, feed pretreatment or the use of hybrid technologies (Bazinet and Geoffroy, 2020; Mikhaylin and Bazinet, 2016b; Nikonenko *et al.*, 2014).

6.4 Electro-activation

Electro-activation (EA) is an electromembrane process allowing the production of solutions having the physico-chemical activity (Gnatko *et al.*, 2011). This activity is acquired due to the relatively severe pH conditions and/or the high or low values of redox potential (Aider *et al.*, 2012). The typical EA cell consists of two electrodes and one or multiple membranes separating the anode and cathode compartments, and can be operated in batch and continuous modes (Aider *et al.*, 2012) (Figure 6.3). In EA technology, the solutions obtained in the electrode sections are normally used compared to previously discussed ED technology in which the solutions obtained in the intermembrane sections are used. One can observe in the Figure 6.3 that two EA solutions can be obtained during the same EA treatment (Aider *et al.*, 2012; Gnatko *et al.*, 2011):

- anolyte (anode compartment) having a low pH (<3) and high redox potential (>1000 mV);
- catholyte (cathode compartment) having a high pH (>8) and low redox potential (<-300 mV).

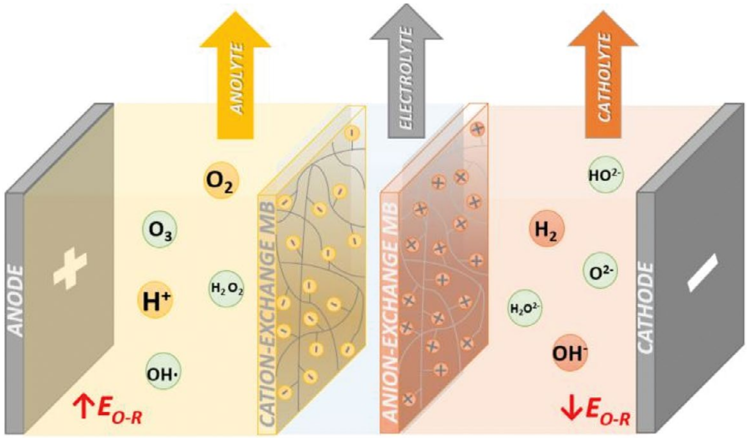

Figure 6.3. Principles of electro-activation process. $E_{O\text{-}R}$ refers to redox potential.

The interesting properties of EA solutions are obtained via electrolysis of water or salt solutions (e.g. NaCl). The results of electrolysis reactions are the following (Gnatko *et al.*, 2011; Sprinchan, 2011):

- generation of protons in anode section of EA cell;
- generation of hydroxyl ions in cathode section of EA cell;
- generation of gases in cathode (e.g. H_2) and anode (e.g. O_2, Cl_2) sections of EA cell;
- generation of highly active metastable oxidizing particles in anode section of EA cell (e.g. O_3, H_2O_2, OH, ClO, ClO_2);
- generation of highly active metastable reducing particles in cathode section of EA cell (e.g. O^{2-}, H_2O^{2-}, HO_2^-).

EA solutions are conventionally used as cleaning agents since they have demonstrated an antimicrobial potential against multiple strengths (e.g. *Staphylococcus aureus, Escherichia coli, Bacillus cereus, Pseudomonas aeruginosa*) (Gnatko *et al.*, 2011). In food industry, the use of EA solutions is still emergent and includes the regulation of enzymatic activity, bread making, control of biofilms and preparation of diverse beverages (Aider *et al.*, 2012; Gnatko *et al.*, 2011). However, in recent years the EA technology has been reported as a promising one for several processes aiming at valorisation of agro-food waste and by-products. For instance, EA technology reported to be effective in valorisation of dairy whey. Indeed, Bologa *et al.* (Bologa *et al.*, 2008) have proposed the use of EA to separate the protein-mineral complexes from whey. Moreover, the *in situ* isomerization of lactose, the main solid of whey, to lactulose (prebiotic and drug (Aider and de Halleux, 2007)) in the alkaline compartment of EA reactor was reported to be effective and less damaging to the environment due to the use of NaCl instead of chemicals (e.g. strong alkali, sulphites, aluminates, borates). Additionally, lactulose can be obtained from electrically treated whey permeate, which is issued after the separation of proteins from whey (Djouab and Aïder, 2019b). The interesting fact is that the EA whey permeate containing lactulose demonstrated a high antioxidant activity (Djouab and Aïder, 2019a). Similarly, Kareb

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et al. (2017a,b) have shown the increase of antioxidant capacity and production of bioactive peptides in EA defatted sweet whey, which means that EA process can significantly increase the value of whey, the important by-product issued from dairy industry. Another example is the application of EA technology for the extraction of diverse food molecules. Indeed, this technology was proved the effectiveness in protein extraction from oilcakes (e.g. sunflower, canola, soybean (Koschaev *et al.*, 2009; Momen *et al.*, 2021)), which are considered as waste or by-products depending on the context (country of oil production, size of the factory, etc.). These protein concentrates were used as functional ingredients in different food formulations (e.g. gluten-free biscuits and functional drinks) (Gerliani *et al.*, 2019; Gerzhova *et al.*, 2016). Moreover, the anolyte, obtained in anode section of EA cell, can be used for pectin extraction from apple and beet pomaces (Shazzo *et al.*, 2005).

Even though there are multiple promising scientific works reporting the application of EA technology to valorisation of multiple agri-food by-products, the scale-up of this emergent technology should be tested in order to verify its eco-efficiency in industrial scale. Moreover, the profound studies should be performed to underline the impact of EA cell configuration and phenomena occurring on the ion-exchange membranes (e.g. transmembrane mass transfer, limiting current density and related coupled phenomena as well as membrane fouling) on the process performance.

6.5 Conclusions

The application of above-mentioned electrotechnologies to the valorisation of a wide range of agri-food wastes and by-products is a very promising and eco-efficient alternative to the conventional resource consuming processes. Indeed, these technologies do not use harmful reagents, have relatively low energy consumption and can be used to attain several goals:

- extraction of valuable compounds;
- separation and concentration of valuable compounds;
- increase of functionality and bioactivity;
- product demineralization.

Hence, the final products obtained by electrotechnologies usually have higher value and can be obtained with lesser environmental impact compared to conventional technologies. However, while several technologies have already attained the industrial level (PEF, ED, EDBM), other technologies are still emergent and need to prove their effectiveness in the pilot and industrial scales (e.g. HVED, EDUF, EA). Moreover, the very promising way is coupling multiple green emergent technologies (e.g. high hydrostatic pressure, ultrasound, ohmic heating) to increase the eco-efficiency of agri-food waste and by-products valorisation.

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