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Review

Bio-refinery approach for spent coffee grounds valorization

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ABSTRACT

Although normally seen as a problem, current policies and strategic plans concur that if adequately managed, waste can be a source of the most interesting and valuable products, among which metals, oils and fats, lignin, cellulose and hemicelluloses, tannins, antioxidants, caffeine, polyphenols, pigments, flavonoids, through recycling, compound recovery or energy valorization, following the waste hierarchy. Besides contributing to more sustainable and circular economies, those products also have high commercial value when compared to the ones obtained by currently used waste treatment methods. In this paper, it is shown how the bio-refinery framework can be used to obtain high value products from organic waste. With spent coffee grounds as a case study, a sequential process is used to obtain first the most valuable, and then other products, allowing proper valorization of residues and increased sustainability of the whole process. Challenges facing full development and implementation of waste based bio-refineries are highlighted.

1. Introduction

Current production and consumption patterns generate large quantities of residues that need to be properly managed, in order to minimize their negative sustainability impacts. For example, in the European Union (EU), each citizen generates about half a ton of waste each year (European Coffee Report, 2017). Combined with industrial, construction and wastes generated by other activities, the EU alone generates more than 3 billion tons of waste each year (EC, 2010). Nowadays it is consensual that a proper waste management helps reduce not only the environmental impact, but also the economic impact, as lower quantities of non-renewable resources are lost and lower amount of energy is used in the production of new goods, and even social impacts, as for example lower degradation of natural environment.

The current strategies and policies concerning waste management are based in the waste hierarchy (WFD, 2008) and a Life Cycle Thinking (LCT) perspective (EC, 2010). Even tough reduction and elimination are in top, in most situations due to practical constraints the generation of waste is inevitable. The next levels of the waste hierarchy involve the valorization of residues, in particular recycling or energy recovery. The first approach tries to recover, as much as possible, materials that have commercial value and that serve as raw materials to obtain new products. The energy recovery is used primarily for combustible waste, in particular the organic fraction of urban waste, and it is used mainly when recycling is not viable, due to the low value of materials recovered, the contamination of the waste materials and/or the large amounts involved and to reduce the quantity of residues landfilled.

To be able to identify which is the best waste management option it is essential to know the amount, composition and frequency of production. Moreover, in the case of recycling, it should be possible to sort the different most valuable components as soon as possible in the process, in order to avoid contaminations that would hinder the use of such compounds for noble applications, such as food and feed industry, pharmaceuticals, etc. Then, going down in the process, it is possible to recover the least valuable components and finally, when there is nothing more to recover, a much smaller amount of waste will need to be eliminated either by disposal in landfills or by incineration, with energy recovery.

Furthermore, to implement a waste management process it is fundamental to have a systemic view of the whole process, starting from collection, including storage and transportation, extraction/recovery of valuable components under the most adequate route, removal of potential contaminants, and finally the recovery of the least valuable materials, resulting in a stream of residues, possibly with some energy content. This approach leads to job creation, increasing the yield and to extend the life of the original materials that will possibly be used for processing more raw-materials, incorporating products from waste treatment in a more sustainable manufacture of new products, developing a circular economy. However, to implement such complex process it must be analyzed the life cycle of each part, in order to assess the adequacy of that component of the process (EC, 2010).

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A way of fulfilling the previous goals is the concept of bio-refinery, in which organic waste streams will be processed to obtain valuable products and energy, to be used for other purposes (de Jong and Jungmeier, 2015; Sadhukhan et al., 2014). Hence, this work presents a bio-refinery approach for treating spent coffee grounds (SCG), produced after beverage preparation at both industrial and domestic contexts, and the possibility of obtaining high value products among others.

2. Bio-refinery: main concepts and importance

In the last decades the need to progress for a more sustainable development, while reducing the environmental impact of production activities and the consumption of non-renewable resources, has forced the industry, policy makers and other stakeholders to look for more sustainable forms of production. In particular, the utilization of renewable resources, for example biomass, and the reduction and proper management of the waste generated are two issues that are being considered in practice. Moreover, there was increased pressure in the industry to be more profitable, thus demanding a rational and efficient utilization of the available resources. This involves not only being more efficient in the production processes, for example by obtaining more products per unit mass of materials used, but also diversify the product mix, in particular of those with high added value. This way it is possible to increase the competitiveness of a company and generate more value from the raw materials it uses.

Several definitions of bio-refinery or bio-refining can be found in literature depending on the activity sector and on the type of biomass used. A consensual and general definition in scope is the one enunciated by the International Energy Agency, "Bio-refining is the sustainable processing of biomass into a spectrum of marketable products and energy" (IEA, 2008). As stated in the definition, the raw materials used in a bio-refinery have an organic biological origin. Thus, they are renewable by definition, as they can be grown and harvested many times within a short span of time. The utilization of a biomass also helps fulfill the goals of a more circular economy, as the raw materials are inherently renewable and are used in a closed cycle, being a good example biofuels. The biomass used to produce biofuels absorbs carbon dioxide on its growth that is released when the fuels are burnt, which is again absorbed by the next biomass to be cultivated and so forth. Moreover, a reduction in the net carbon emissions is observed, helping to reach the goals defined by the Paris Agreement (UNFCC, 2016).

Recognizing the role that bio-refineries and the bio-based sector can play in a more sustainable and circular economy, several research, development and industrial realization programs were implemented involving stakeholders from academia, industry and policy making organizations, among others. Examples include the EU Bio-Based Public-Private Partnership (https://www.bbi-europe.eu/), the NREL Integrated Bio-refinery Research Facility (https://www.nrel.gov/bioenergy/) and the IEA Task 42 (http://www.iea-bioenergy.task42-biorefineries.com/en/ieabiorefinery.htm). Bio-refineries are currently a very important area, with significant investments being made not only in research but also in the practical implementation of the concept.

All types of biomass may be used in a bio-refinery, as for example microalgae, wood, lignocellulosic biomass and organic waste (Kwon et al., 2013; Mata et al., 2012a, 2014a; Ribeiro et al., 2015; Sadhukhan et al., 2014, 2015). The final products strongly depend on the characteristics of the raw materials and processes involved and may have various applications (Obruca et al., 2015; Pandey et al., 2000; Safarik et al., 2012; Severini et al., 2017; Zuorro and Lavecchia, 2012). A form of classification is the 4F's economy (Poltronieri and D'Urso, 2016): Food, if the product is intended for human consumption; Feed, for animal consumption; Fuel, for energy, either electricity heat or an energy carrier such as biogas; and Fiber, for materials and/or compounds that can be used in other process industries to obtain other products. Thus, the concept of a bio-refinery is similar to a petrochemical refinery, in which biomass plays the same role as oil. In particular, besides obtaining several products, a bio-refinery combines various types of processes and unit operations to process the biomass (de Jong and Jungmeier, 2015; Sadhukhan et al., 2014). Both physico-chemical (e.g. gasification, pyrolysis, solvent extraction, etc.) and biological (e.g. fermentation, anaerobic digestion, etc.) conversion pathways can be used (Kida et al., 1992; Namane et al., 2005; Pandey et al., 2000). Also, many of the separation processes and unit operations, already used in a petrochemical complex, can be used on a bio-refinery (de Jong and Jungmeier, 2015; Sadhukhan et al., 2014). Although this state of affairs may help and support the practical implementation of bio-refineries, much still has to be done in terms of process development and design. Important issues still under study involve process integration, how the supply and distribution chains can be combined with the production process, suitable pre-treatment and treatment strategies, among others (Girotto et al., 2017; Kwon et al., 2013). A more complete description and classification of bio-refineries is outside the scope of this work, and can be found in the literature (de Jong and Jungmeier, 2015; Sadhukhan et al., 2014).

From a sustainability point of view a bio-refinery should be projected, implemented and operated within a LCT framework, starting with the acquisition of the raw materials, processing and production of valuable products, distribution and waste disposal, that includes the residues generated in the bio-refinery (Mata et al., 2014b). As bio-refineries are an emergent industrial sector, there is still time and opportunities to identify which raw materials, processes and final applications are more adequate to ensure that the most sustainable options are chosen (Caetano et al., 2017). In particular, the availability of raw materials is a key issue that should be considered with care. Important aspects include not only the availability and cost, but also the supply sustainability and the market potential for the products obtained from the biomass. For example, oleaginous crops can be used to produce biodiesel, but significant environmental impacts may occur due to the cut of tropical forests with loss of biodiversity and even social and economic problems due to the occupation of arable land that may be used to produce food (Mata et al., 2012, 2013). The remaining life cycle stages are also very important, but in a certain way the set of processes and potential products that may be obtained are in essence defined by the nature of the biomass and/or the organic raw materials used in a bio-refinery.

The utilization of organic waste, either resulting from domestic or industrial activities, in a bio-refinery makes sense from a sustainability point of view (Caetano et al., 2012, ; Mata et al., 2015; Sadhukhan et al., 2014, 2013). First, it represents a very significant amount of waste, comprising residual biomass from forest operations, food waste, and agricultural residues, among others. Failure to treat this type of waste can lead to significant health and safety problems, with important impacts in the daily lives of people. In a European context a considerable percentage still goes to the landfill (Eurostat, 2017). Taking into account the waste hierarchy (WFD, 2008) better forms of treatment are available that allow an economic valorization of organic waste. In particular: anaerobic digestion that produces biogas for energy generation (Dinsdale et al., 1996); composting that produces compost for agricultural application (Ribeiro et al., 2017); and incineration with energy recovery (Silva et al., 1998). Each one has limitations on the type of raw materials that can be used and the final products have low added value.

Yet, organic waste is a complex mixture of compounds, including sugars, proteins, amino-acids, fatty acids, among many others, that have a plethora of potential applications in various areas (Murthy et al., 2009; Panusa et al., 2013; Passos et al., 2014; Shang et al., 2017). Some of them are already produced using chemical processes and non-renewable resources, a situation that is clearly non-sustainable. Organic waste may be a source for some compounds that are both cheap and sustainable and the continuous human consumption provides a steady supply of raw materials. Moreover, waste collection and separation can also be a significant issue, in particular for those residues that are