ECONOMIC, SOCIAL AND ENVIRONMENTAL IMPACTS ATTAINED BY THE USE OF THE EFFLUENTS GENERATED WITHIN A SMALL-SCALE BIOREFINERY CONCEPT

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Abstract
Biorefineries are emerging as the proper route to defeat climate change and other social, socio-economic and environmental concerns. So far, no residual lignocellulosic biomass-based biorefineries have been yet industrially implemented, mainly due to its economic viability. This article exposes some elements that may help overcome the bottlenecks associated to its social, economic and environmental sustainability: small-scale approaches, biomass valorisation through added-value products and near-zero effluent.

Keywords
biorefinery; biomass; effluents; economic; sustainability; impact

Introduction
The energy sector stands out for its significant impact and transversal role it plays in all other economic sectors, sustainable development, and challenges identified under the European Strategic Plan for the Energy (SET-PLAN). The energetic valorisation of biomass, as renewable natural resource, intends to play a role central to the future of Energy Policies, in particular for the decarbonisation of the transport sector and its more efficient use in the production of electricity and in the heating and cooling.
Fossil fuels depletion and climate change, as well as the current global energy demands require the search for suitable bio-substitutes for the products currently being obtained from fossil sources [1]. In the EU context, the Renewable Energy Directive (RED II) has established a share of 32 % as the overall target for Renewable Energy Sources consumption by 2030, with a minimum of 14 % of the energy consumed in road and rail transport coming from renewable energy [2]. This directive also defines some sustainability and GHG emission criteria. For instance, in the case of transport biofuels, after January 2026, a minimum of 65 % GHG reduction must be achieved in comparison to reference fossil fuels. Similarly, considering that biofuels production may lead to the extension of agricultural land into non-cropland and negatively affect areas with high carbon stock, indirect land use change (ILUC) issues have also been included and regulated in RED II.

First-generation (1G) biofuels suffer of important drawbacks to meet those criteria due to the high water and energy consumption needed during their production and the negative side effects on the food market. Hence, during the past decade there has been a growing interest in developing biofuels and bioenergy carriers non-linked to the food sector. For biofuels productions (e.g. bioethanol), the use of residual lignocellulosic biomass (second-generation, 2G ethanol) instead of food crops (1G ethanol) can lead to lower environmental impacts (and no competition with food crops) [3]. In this line, and within the 14 % transport sub-target, RED II has established that the contribution of advanced biofuels should be of at least 3.5 % in 2030 (Fig. 1). This category represents biofuels produced from non-food related and sustainable feedstocks, such as energy crops, algae and wastes, as well as agricultural and forestry residues.

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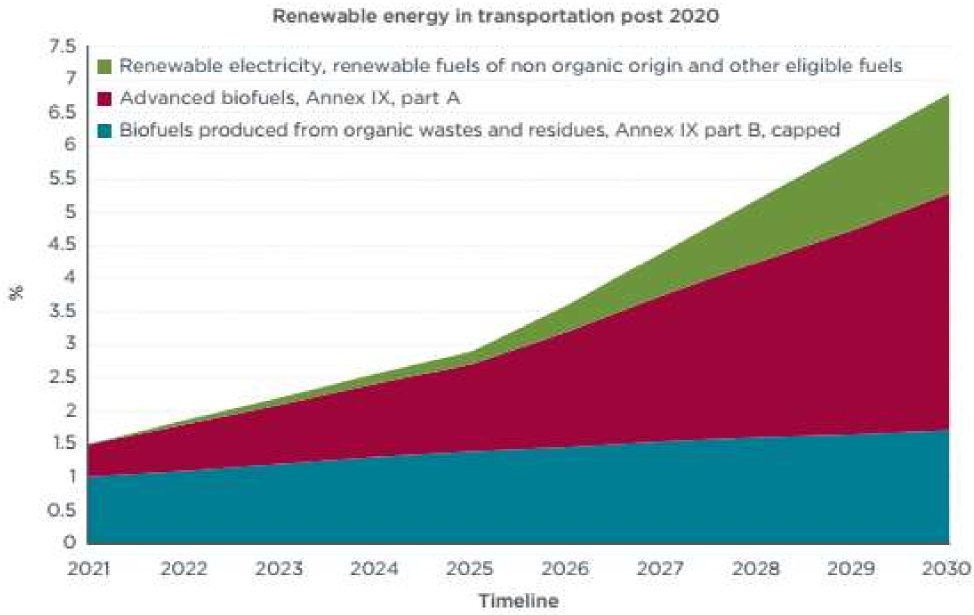

Fig. 1. the RED II requirement for fuel suppliers to have a 1.5% minimum energy share for the overall renewable energy mandate beginning in 2021, which includes a 0.5% minimum share for advanced biofuels produced from the feedstocks listed in Annex IX, Part A. The overall share of biofuels produced from Annex IX, Part B, can be smaller than 1.0%–1.7%, as indicated in the figure. *Source: The European Commission's Renewable Energy Proposal For 2030, ICCT - International Council on Clean Transportation, January 2017* [4]

One way to overcome these concerns is the development of biorefining processes to produce biofuels and bioproducts with a lower global warming potential (GWP). A biorefinery is an industrial installation that optimises the full use of biomass (raw material) in a sustainable way giving rise to a diverse range of products, namely biofuels, energy, biomaterials and chemicals (end-use or intermediates). It has evident similarities with a refinery that uses fossil resources (e.g. oil) and in certain situations, constitutes a viable alternative to replace oil with biomass. Although the characteristic of a biorefinery is a multi-product industrial unit, like an oil refinery, its integrative design varies among those that are primarily energy-based, that is, in which the industrial unit is optimized primarily to generate bioenergetic products from biomass, namely biofuels, electricity and heat, generating simultaneously co-products that could be precursors of products of greater added value for non-energy applications; and those that are optimised for generate mostly bioproducts (biomolecules, intermediate chemicals) and biomaterials from biomass and in parallel only a minority fraction of the biomass is diverted to production biofuels, electricity and/or heat, as that is not the main purpose of a biorefinery. Biorefineries have primarily followed the concept of classical oil refineries, using a single feedstock in huge processing capacities to achieve maximum economy of scale, but under such framework, the opportunities for installing such biorefineries in most rural areas in Europe and even worldwide are scarce. Studies have revealed that the main bottlenecks are associated to high CAPEX and OPEX, and very often to the inexistence of a sustainable biomass supply at regional level [5].

Small-scale biorefineries have been proposed as a potential solution to overcome most of these challenges, since when located in rural areas they can promote territorial economic cohesion and generate local direct and indirect jobs [6,7]. Small-scale also allows a reduction in transportation costs of raw materials and intermediate products and leads to a direct link between industry and the primary sector. Despite the strategic relevance of small-scale biorefineries, numerous technological and strategic challenges still hamper commercial development, namely the heterogeneity of the biomass resources for further processing [8].

Furthermore, several studies have proven that in order to become economically and environmentally viable, it is almost mandatory that these small-scale biorefineries valorise all the available effluents (waste waters, gas emissions, waste solids, etc.) for producing additional added-value products and reduce the consumption of external energy sources [9–12]. Lopes et al. [13] have demonstrated that for a microalgae-based biorefinery,

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using a genetically modified cyanobacteria for direct production of ethanol, the process is only economically viable when the pigments and proteins obtained from microalgae biomass are recovered, and the spent biomass sent to anaerobic digestion for biogas production and subsequentially used in co-generation. Susmozas et al. [14] also state that for a small-scale biorefinery using olive tree pruning as feedstock, the bioethanol production together with the integrated by-products production (xylitol and antioxidants) is technically and economically viable, and the energy demands are reduced by power and steam co-generation from combustion of residual solid material and methane produced by anaerobic digestion of wastewater.

Process modelling and simulation using software-based tools is a useful methodology to ascertain process feasibility at scales larger than laboratory scale, such as pilot, demo and industrial scales [10,15,16]. The use of process modelling to study biomass processes for the production of high added-value products has certain limitations on evaluating scalability and replicability. Usually, process modelling is based in black-box models where process yields are taken from the literature or from experimental data, so they cannot evaluate the consequences of changing feedstock properties, process parameters and operational conditions. Thus, there is an inherent need of knowing more about the fundamentals of these processes:

- biomass composition models using realistic and predictive models, where biomass reactivity can be represented by the reactivity of a series of surrogate molecules
- actual predictive models that can predict the mass and energy balances of biomass-based processes through kinetic, thermodynamic and semi-empirical models.

These approaches allow the evaluation of different scenarios, assessing which pathway is the most adequate when upscaling a biorefinery, for the process to present lower CAPEX and OPEX, and for lower environmental and social (negative) impacts.

As an example, it is known that in rural temperate and humid tropical regions, most biomass resources are crop and food residues, animal and human waste and agro-processing residues. One way to take advantage of this heterogeneity is by combining two different biorefinery platforms: the biochemical platform transforming lignocellulosic feedstock into sugars and then into biofuels and/or added value chemicals, and the anaerobic digestion platform converting wet biomass into biogas [17]. Such a small-scale integrated biorefinery should be able to transform both dry and wet biomass residues by means of different processes to produce an array of bioproducts, maximizing the resources, the energy efficiency and the environmental sustainability of the whole value chain. Lopes et al. [9] have shown through a comparative process modelling and simulation study that, by combining these two different platforms (lignocellulosic-based small-scale biorefineries, integrated with a piggery waste-based anaerobic digestion platform, located in Portugal and Chile – Fig. 2), the isobutene/xylo-oligosaccharides (XOS) biorefinery concept is proven to be economically viable in both countries, mainly due to the high market value of XOS, and is a flexible process that can be implemented in any of these countries, even using different lignocellulosic biomass as feedstock (wheat straw and corn stover).

Therefore, techno-economic analysis (TEA) of biorefineries as well as life cycle assessment (LCA) are two powerful tools to evaluate the expected impacts (social, economic and environmental) of implementing innovative bio-based conversion routes for the production of biofuels and/or bio-based products. Usually these assessments are bioenergy-driven, and tend to demonstrate that its economic viability is highly dependent on the main product market price or by significantly reducing the energy consumption of biomass fractionation or downstream processing units (e.g. hydrothermal biomass pre-treatment, ethanol/water distillation process). Furthermore, by funnelling the biomass conversion entirely to biofuels, there are two main bottlenecks: market-dependency and excess of effluent streams to be treated (gaseous, liquid or solid). The former is extremely oscillating and with a decreasing trend on biofuels market price, the latter generates higher CAPEX and OPEX for waste treatment and additional negative environmental impacts. To overcome these drawbacks, it is of extreme importance to valorise all the biomass fractions and perform mass and heat integration to reduce or eliminate the effluent streams

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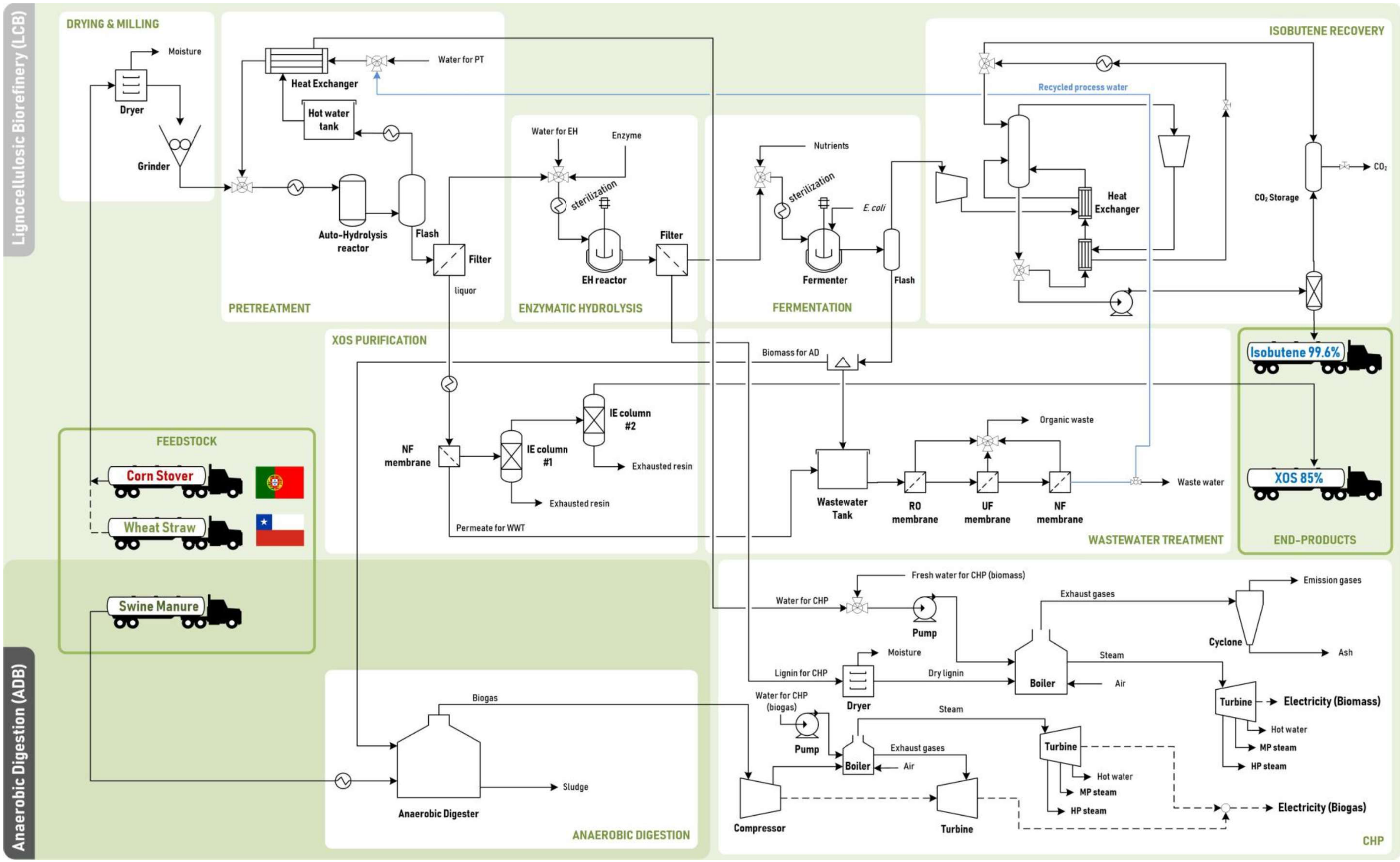

Fig. 2. Example of an integrated small-scale biorefinery concept for valorisation of all streams. *Source: Adapted from [9]*

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Agricultural and forest residues, like any other plant biomass, consist of three main macromolecules: cellulose, hemicellulose and lignin [18]. To efficiently convert this biomass feedstock into biofuels (such as 2G bioethanol) and bioproducts (biorefinery-driven), pre-treatment is the first technological operation, in order to make the biomass susceptible to hydrolysis with the aid of enzymes. The resulting C6 sugars syrup is then fermented and transformed into 2G bioethanol, higher alcohols, or bio-based products. C5 sugars can be fermented together with C6 sugars (using recombinant strains) or upgraded into, for instance, prebiotics (e.g. XOS). Lignin can be burned to generate steam (and therefore reduce the energy demand and the use of fossil sources) or preferably can also be valorised into added-value products (e.g. vanillin, benzene-toluene-xylene, syringol, carbon fibres or activated carbon). Mass integration through the re-use of carbon dioxide effluent streams from fermentation for microalgae cultivation, anaerobic digestion of waste water streams for biogas production or upgrading, use of biomass ash as in-situ catalyst, are interesting and promising options to reduce the impacts of such technologies. Heat integration between stream processes is also one of the most adequate pathways for taking advantage of biorefineries flexibility, leading to a considerable reduction on energy consumption.

Impact

Considering the economics of advanced biorefineries, it is necessary to warn that in the more restricted scope of advanced biorefineries focused on energy recovery, they almost all require incentives through stable medium and long-term legislative measures. In particular, the cost of production of advanced biofuels depends mainly on the cost of biomass (raw material), investment cost and operating cost. The latter two are higher than the CAPEX and OPEX costs of first generation biorefineries (e.g. FAME biodiesel units). Among others reasons, the costs of collecting and transporting biomass are important to be considered in the initial planning phase of biorefineries, so only the value chains based on low cost, zero cost or residual biomass negative can currently offer the production of bioenergetic products competitive.

Furthermore, the economic impact attained by the use of effluents generated within a biorefinery concept is reflected on the reduction of additional investments costs in equipment for waste treatment, a reduction on operating costs (e.g. raw materials, utilities, maintenance) by lowering the needed volumes to be processed, achieving high energy-efficient yields on raw materials recovery and recycling, lowering the logistic and supply chain costs by using a small-scale biorefinery concept and therefore create local synergies with suppliers and end-users, without the need of utopic processes.

Additionally, a small-scale biorefinery concept taking advantage of all the generated effluents and valorising the biomass fractions generate much lower GHG emissions (virtually zero), have a significant impact on fossil fuels depletion (no fossil sources are needed – a small-scale biorefinery has the potential to be energy-sufficient), water depletion (a huge amount of fresh water needed is reduced by waste water recycling and purification), eutrophication and toxification (almost no toxic waste for soils and water is generated).

An adequate biorefinery design is crucial to prevent the toxic effluents and GHG emissions as in oil refineries design, where negative environmental and social impacts were obtained during oil processing and products use. Nevertheless, sustainable biorefinery systems are still a challenge since weak designs lead to processes hardly operating on the economic margin, not providing significant reduction of environmental burdens in comparison to petrochemical systems and facing socio-economic issues due to endless discussion on land use, labour, food safety, etc. The diversity of bioproducts that can be obtained from biomass under the biorefinery concept lies under the umbrella of bioeconomy. As Moncada et al. state: "A biorefinery is a complex system, where biomass is integrally processed or fractionated to obtain more than one product including bioenergy, biofuels, chemicals and high value-added compounds that only can be extracted from bio-based sources. The latter after a comprehensive study of the raw materials to be used and a sustainable design based on the latest state of the art technologies and approaches which include aspects of the three pillars of sustainability" [19]. Hence, in order to catch the same train as the European Commission and other policy makers, bioenergy and biorefinery researchers and players should look at these (near zero waste) small-scale biorefineries as a promising solution to a worldwide concern.

Another aspect in the small-scale advanced biorefinery development is territorial cohesion and territorial enhancement. It contributes to reduce the gap in the implementation of technology-based industries between more developed regions and generally less developed rural areas where biorefineries can boost either qualified employment and technology enhancement. However, the existence of residual biomass available in a given region is not in itself synonymous with the economic profitability of a biorefinery in that region. It is necessary

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to assess the constraints of your supply chain, alternative markets and industrial infrastructures in the biomass sector, which may already exist in that region that allows for the enhancement of local synergies, among others.

Conclusions

The 2030 horizon is the tolerable limit for implementing advanced biorefineries, focused on bioenergetic products, from residual biomass or with a lower economic value. Namely, biomass agroforestry waste or in the co-valorisation of biomass in industrial value-added bioproducts, obtained with or without biochemical or thermochemical processing of any other organic biomass provided it does not compete with the human food markets and within the so-called bioeconomy.

The valorisation of effluents is very likely to be a good option for GHG emission reduction. However, for reasons of fair competition, LCA methodologies should be applied in an identical way to assess the sustainability of both energy- and any other non-energy basis biorefineries, namely in terms of comparative measures to reduce GHG emissions.

Conflict of interest

There are no conflicts to declare.

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