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Key challenges and requirements for sustainable and industrialized biorefinery supply chain design and management: A bibliographic analysis

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ABSTRACT

The growing global population and its effects on world food security, as well as the urgency for climate change mitigation, are issues that foster technological, social, and political innovations to increase the efficiency of use of natural resources, such as biomass among others. While significant research efforts have been devoted to biomass conversion processes, their associated supply chains and their implication for complete process efficiency have only been studied more recently. However, most of the recent investigations into the design and optimization of biomass supply chains have focused on an economic point of view, sidelining other dimensions of sustainability, which represents a serious drawback for this kind of work. This article surveys the recent research on design and management optimization of biorefinery supply chains from a sustainability perspective. 72 published research articles from 2006 to 2015 have been analyzed to highlight the sustainability dimensions considered, as well as the inclusion of uncertainties. A typology of decision-making at three levels of analysis (strategic, tactical and operational), and the specific set of tools used to model and optimize the biorefinery supply chain have also been studied. The conclusion underlines the contributions and shortcomings of current research and suggests possible future directions.

1. Introduction

The growing global population and its effect on world food security, as well as the urgency for climate change mitigation, are issues that foster technological, social, and political innovations to increase the efficiency of the use of natural resources [48,94,109]. Among the natural resources, biomass has interested researchers because of its widespread availability and its potential applicability as a sustainable source of energy and material [109]. In order to take advantage of the biomass potential, new technologies have been developed to generate alternative energies and new materials, which have the potential to reduce greenhouse gas emissions, while increasing energy security and sustainability [52]. With the aim of integrating these raw materials and technologies, biorefineries are designed to transform biomass into a range of marketable products and energy [24,94].

Nevertheless, in order to use biomass at an industrial scale and in a sustainable manner, a well-designed and well managed supply chain (SC) is a key condition [30]. Indeed, the design and management of such a project involves many hierarchical decisions which should be optimized [57]. The SC design, management and optimization is a highly complex problem that cannot be solved using simple heuristics from the viewpoint of a single discipline [94].

Recently, many researchers have focused their work on the process of design and optimization of a Biorefinery Supply Chain (BioRSC) from an economic point of view [103,128]. However, the other two traditional dimensions of sustainability have not been included, which represents a serious drawback for this kind of project. In order to overcome this problem, the objective of the present work is, through a comprehensive mapping of the scientific literature, to identify the key research challenges and requirements for BioRSC design and management optimization from a sustainable point of view.

182 research articles published from 2006 to 2016 were found and revised. Among them, 84 significant references in terms of sustainable biorefinery supply chain design and management were selected. This review distinguishes between the existing surveys by adopting a sustainability perspective, emphasizing the BioRSC challenges, the dimensions of sustainability involved and the solution methods employed.

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As a starting point, Section 2 proposes an overview of the BioRSC: the description, challenges and requirements are presented. Section 3 describes the applied methodology for this mapping study. Section 4 presents a comprehensive overview and classification of the existing contributions on BioRSC optimization and simulation. To conclude, the principal results focusing on the set of sustainability dimensions considered are discussed in Section 5.

2. Biorefinery background, challenges and requirements

As the biorefinery concept includes different industrial sectors, there is no single definition. However, based on the definitions provided by institutions such as the National Renewable Energy Laboratory [85], the Energy Research Center of the Netherlands [29] and the National Non-Food Crop Centre [84], a general definition of the biorefinery concept could be proposed:

A biorefinery is a facility similar to the traditional oil refinery, where energy, fuels, chemicals and materials are produced through different processes and technologies. Nonetheless, a biorefinery's raw material is any organic material from renewable sources that can be used for industrial purposes. Consequently, there are numerous possibilities for converting it, which multiplies the possible schemes of operation that can be developed.

Biorefineries' main raw material is biomass, that is organic material obtained from living or recently living organisms, which can be used for industrial purposes [37,53]. Because of the diversity of biomass resources, multiple conversion technologies are needed to transform the physical and chemical properties into the broad range of feedstock materials [10]. The products obtained in a biorefinery could be energy, fuels, chemicals or materials [24,51,85]. The diverse biomass types, processing technologies and end-products involved in a biorefinery are summarized in Table 1.

Regarding the wide range of raw materials entering the production system and the diversity of processing technologies, three degrees of biorefinery integration can be distinguished, as presented in Fig. 1 [53,114]. A "Phase I" biorefinery uses a single raw material in a simple and fixed transformation process, yielding one main product. A "Phase II" refinery also processes a single raw material, but is able to produce various end-products in response to the market and the plant's operating limits. Finally, a "Phase III" refinery uses several types of raw materials and production technologies that enable the production of many industrial products.

Table 1
Raw materials, processing technologies and products in a biorefinery (adapted from [20,23,50,128]).

Biomass	**Transformation technologies**	**Products**
Residual Biomass	*Physical transformation*	*Energy*
Forest residues	*Direct extraction*	Thermal energy
Agricultural residues	*Biochemical transformation*	Electrical energy
Municipal waste	*Thermochemical transformation*	Mechanical energy
Energy Crops		*Biofuels*
Crops for ethanol production		Bioethanol
Oilseeds		Biodiesel
Lignocellulosic crops		Biogas
Aquatic crops		Synthetic biofuels
		Chemicals and materials
		Carbohydrate-based bio-products
		Lipid-based bio-products
		Protein-based bio-products
		Lignin-based bio-products
		Secondary metabolites

While "Phase II" and "Phase III" biorefineries are able to respond more rapidly to changes in the market environment than a "Phase I" biorefinery, their SC design is more complex. There is definitely a set of choices to make that increases the decision-making process. Once the final product features and requirements are defined, these decisions must include biomass selection, transformation technologies and materials management for turning raw materials into end-products, in addition to other constraints and requirements for developing a sustainable biorefinery, which will be discussed subsequently.

2.1. *Challenges and requirements for a sustainable biorefinery supply chain*

As in any other design journey, goals and constraints must be managed in order to explore the solution spaces to develop a biorefinery on an industrial scale and in a sustainable manner. As stated by Ekşioğlu et al. [30] and [35], a well-designed and well managed SC is needed. Hence, designing and optimizing the entire BioRSC system from biomass feedstock production to bio-based products must be developed in a cost-effective, robust and sustainable manner [8,128]. In order to accomplish this task, the constraints and requirements that should be taken into account could be classified into three main groups: those related to the BioRSC nature, including evaluation of the sustainability dimensions, and those related to the decision-making stages, which will be described in the following.

2.1.1. *Constraints generated by the biorefinery supply chain's own nature*

First of all, **biomass** is usually characterized by seasonal availability [91]. At the same time, there are high transportation costs because biomass is bulky and difficult to transport. Moreover, harvesting and collection costs are high because their supply is widely dispersed geographically [30]. Moreover, biomass is a heterogeneous matter, so it requires pre-treatments to homogenize it [96]. Therefore, the form in which biomass will be procured determines a high percentage of the investment and operational costs.

Another characteristic of BioRSC is the **distributed nature of members**, which means that organizations in SC are independent and also geographically distributed [47]. This implies that each stakeholder regards its own interests and needs, and focuses on achieving its own targets [71]. Therefore, a previous geographical analysis is required, in addition to an analysis for the interest of stakeholders, which is clearly associated with multi-objective management. These members, as in all SC systems, interact strongly, thus the system exhibits a wide range of **dynamic behaviors,** which can interfere with scheduling and control at the enterprise level [67]. This dynamic behavior is due principally to the competitive environment [119].

The set of constraints detailed above adds strong **uncertainties** that affect the efficiency of the BioRSC system, which eventually can lead either to infeasible supply chain network designs or to suboptimal performance [39]. These constraints create a complex landscape for biorefinery investors and decision-makers, and consequently tools are needed to help assess these uncertainties [58]. A detailed list of these uncertainties and their origin is presented in Table 2.

The tools to assess these challenges should consider that BioRSC requires **information sharing** by rapidly transferring information about customer demand to all SC levels [47], as this enables rapid response to market changes [82]. Similarly, a **flexible** structure is desirable, for example a SC that adapts itself to environmental changes [47].

2.1.2. *Evaluation of the sustainability dimensions*

BioRSC design also requires sufficient covering of all aspects of a

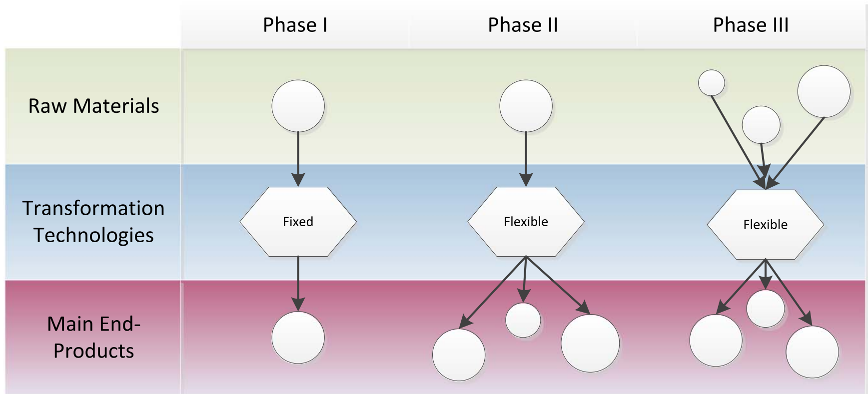

Fig. 1. Degree of biorefinery integration based on [53,114].

Table 2
Biorefinery supply chain uncertainties [58,103].

Classification	Uncertainties
Cost	Cost of transporting biomass Operation cost for conversion processing Cost of transporting intermediate products Cost of transporting final products Acquisition cost for each biomass type Annualized capital cost of conversion processing Expansion plans
Profits (Value)	Value of each intermediate product at conversion processing site Sale price of each final product
Production Process	Yield of final product from intermediate product at conversion processing Yield of intermediate product from biomass at conversion processing
Extern	Demand fluctuations Natural or human disasters Weather Technology availability Change in regulations and policies
Nature of biomass	Biomass availability for each biomass type Biomass properties such as moisture content

sustainable SC and development of an adequate and realistic representation. This means providing a holistic point of view [1], considering, for example, that biodiesel production is not currently economically attractive in comparison to the price of diesel [120], although there are benefits in other fields, such as environmental, that must to be simultaneously considered.

The adoption of sustainability assessment for the BioRSC design from a holistic point of view should consider the relevant/full range of "dimensions" of impact, since decision-makers and other stakeholders should be informed of the full spectrum of impact [8]. In terms of dimensions of impact, the environmental, social and economic dimensions are sometimes referred to as the "three pillars" of sustainability or the "triple bottom-line – TBL" [13,101]. Moreover, recently, the Triple Bottom Line Extended (TBL+) was proposed, including the political and technological dimensions for biodiesel sustainability analysis. TBL + could also be applied to any type of biorefinery.

In particular for these types of systems, the political dimension is highly relevant because the Government's policies are essential for promoting biodiesel production, creating economic conditions and favorable markets such as subsidies, tax exemptions, and compulsory consumption as in the case of the diesel-biodiesel mixture [8]. Moreover, the technological dimension is also relevant, taking into account that in the field of bio-based products emerging technologies are coming out, and there are concerns about technological learning, royalties or technology substitution among other things [8]. This new concept can be enlarged to biorefineries, because biodiesel constitutes part of the “Phase I” biorefinery. Therefore, five dimensions of analysis should be considered to determine sustainable design criteria and optimization objectives, as discussed as follows:

2.1.2.1. Economic. The main economic objective is to design a self-sustaining biorefinery, i.e. it does not need government assistance or reinvestments, because it has the necessary profitability to be self-sustaining [16]. Several metrics can be used to measure this objective, but in this case it is necessary to evaluate indicators such as “Maximizing Profit” or “Net Present Value” because minimized cost metrics are not really useful, since the high production cost of biodiesel, for example, is mainly due to the acquisition cost of raw materials [92]. Also, due to changes in prices and market volatility, it is important to include product diversification and the sale of by-products [124].

2.1.2.2. Social. Regarding the social dimension, studies conducted on BioRSC have measured two edges: the first is related to employment generation and the second to social welfare in terms of food security [6,105]. However, the topics considered in the social dimension must also include respect for property land rights, social acceptability, and promotion of responsible working conditions [8].

2.1.2.3. Environmental. Among various approaches, life cycle assessment (LCA) is the one most utilized in studies that consider environmental impact [128]. The environmental principles considered in this dimension can be analyzed in regard to issues such as air, soil and water quality, waste and wastewater management, balance of greenhouse gases, conservation and protection of biodiversity and wildlife, and energy efficiency [93].

2.1.2.4. Technological. The technological dimension refers to the production technologies available on the industrialized and developing level as well as its evolution through technological learning based on production [22]. It also takes into account technological trends in the use and production of bio-based products.

2.1.2.5. Political. This refers to promotion or restriction policies that may be promulgated by governments of each country, as well as possible subsidies and tax reductions to stimulate the market [8].

This dimension is one of the most important for a biorefinery because through governmental incentives several countries, for example Colombia, Brazil, Argentina, Peru [34,116], the USA [112] and the European Union [33], among others, have developed suitable conditions for industry emergence of biofuels and bio-based products.

This enlarged vision of the TBL, enalbing an improved analysis of the implication of a biorefinery within a particular context. However, the main challenge associted to increasing the dimensions of the sustainability analysis is the availability of reliable information to accomplish it. In addition, in terms of BioRSC modeling, it involves integrating a greater number of variables, parameters, objectives and constraints that may require longer times calculation for optimization and / or simulation.

2.1.3. Requirements for decisions involved in the design and management of the biorefinery supply chain

In addition to previous challenges and requirements, the design and operation of SC networks are also an important and challenging aspect for the industrialization of biorefineries [57]. SC refers to an ideal complete management system as a single entity and not as a disparate group of functions [11,55]. Consequently, the principal challenge in managing SC is the development of decision-making models that can accommodate multiple stakeholders and activities integrated across the SC network [115].

The decision-making process across the various activities of the SC is hierarchized under three decision perspectives: strategic, tactical and operational [80]. The strategic decisions are the basis for tactical and operational decisions as shown in Fig. 2. The strategic level covers long-term decisions in the SC design [19,21,72], while the tactical level includes the management of medium-term decisions (monthly), which typically range from six months to one year [3,44]. The operational level corresponds to short-term decisions, weekly and daily, which concern inventory planning (daily inventory control, lack of inventory at distribution points) and programming vehicles [111].

3. Methods

Regarding the need to use biomass in a sustainable and industrialized manner, the objective of this mapping study is to determine how the key challenges and requirements for sustainable BioRSC design and optimization have been addressed by the scientific community. Thus, a systematic literature review method composed by a search strategy and analysis of the collected documents has been deployed.

3.1. Search strategy

In order to determine how the key challenges and requirements for sustainable BioRSC design and optimization have been addressed by other researchers, a search strategy was designed including the following steps: (1) keyword definition to perform the search in databases, (2) establishing sources of information to be employed (databases), (3) delimiting the period to be explored, and (4) making an initial selection of documents.

3.2. Descriptive document analysis

After the first filter, the selected documents were analyzed in terms of inclusion of challenges and requirements, as well as what types of tools have been used for SC design and management.

As the challenges generated by the nature of BioRSC are part of the uncertainties that affect BioRSC system efficiency, we decided to (1) analyze the inclusion of uncertainty in the model used for SC design and management as the first descriptive analysis. Then, (2) the presence of any of the five dimensions of sustainability and (3) the decision-making levels and major decision variables included in the research were analyzed for comparison.

4. Results

According to the search strategy described above, 182 scientific publications were found thanks to the selected keywords. Then, after a first selection, eighty-four scientific publications were chosen to be reviewed in detail. Fig. 3 presents the distribution of analyzed publications according to their scope (Economic, Environmental, Social, Technological or Political), the applied approach (simulation and/or optimization) and the considered decision levels (Strategic, tactical or operational). It appears from the figure that studies focused exclusively on “economic” objectives are the most common (30) and mostly deal with optimization only. On the opposite side, the “political” dimension of sustainability is the least studied, with only five publications that included government incentives. Furthermore, 51% of publications include the three decision-making levels.

It is noteworthy that most of the investigations have been applied to cases in the USA. The remaining publications have been applied in countries like Spain, Colombia, Greece, and Iran, among others. Thus, there is a real need to increase internationalization of the application of both bio-based products and models that facilitate the implementation of these industries.

The approaches used on the analyzed documents were optimization, simulation or both. The optimization determines the values of the decision variables that optimize (minimize or maximize) an objective

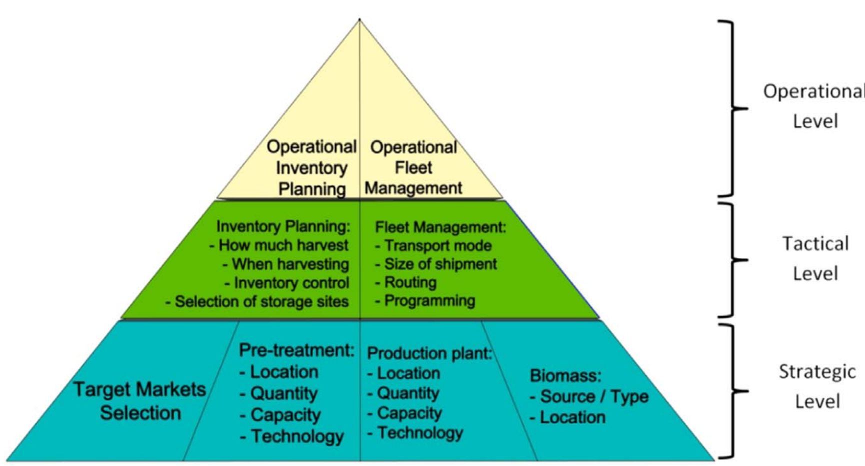

Fig. 2. Main decision variables for each level of decision-making in BioRSC management [50,80].

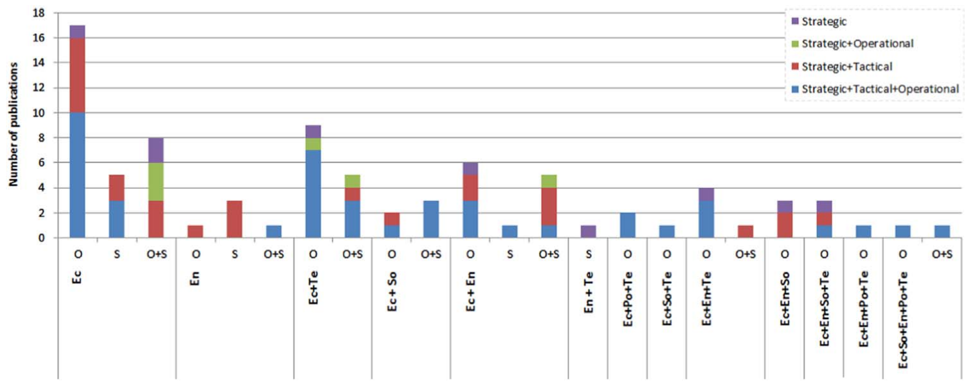

Fig. 3. Publication distribution according to the three levels of classification regarding scope (Ec=economic, En=environmental, So=social, Po=political, Te=technological) and approach used O=optimization, S=simulation).

Table 3
Search strategy steps.

Steps	Description
Keywords	"Supply Chain" AND "Biorefinery"
Sources of information	Journal articles and conference proceedings searched in databases in English. Specifically in Scopus and Web of Science.
Period of information	Between 2006 and 2016, because the first documents found referring to biorefineries date back to 2006.
Initial selection (First filter)	Document selection related to the whole BioRSC modeling

function over a set of values that satisfy a set of constraints [121], while simulation seeks locally optimal solutions, not necessarily global, to reduce execution times and deal with the complexity and stochastic relationships between variables that represent a system [121].

Furthermore, Table 4 presents a detailed analysis of each publication reviewed. First, they are divided by the set of included dimensions. Thus, there is the "Mathematical Optimization" approach, the "Simulation" approach or both. In the next column (specific tool) there are the specific tools used. For mathematical optimization are "Linear Programming" (LP), "Mixed Integer Programming" (MIP), "Mixed Integer Linear Programming" (MILP), "Mixed Integer Non Linear Programming" (MINLP), "Stochastic Mixed Integer Linear Programming" (SMILP), "Mixed Integer Quadratic Programming" (MIQP), "Non Linear Programming" (NLP) and "Mixed Integer Linear Fractional Programming" (MILFP). "Multi-objective" (MO) optimization was used in cases where there are more than one objective function. Simulation has been carried out through "ASPEN," "Arena" and "Extended tm" to represent the chemical processes of production, material and information flows and possible routings between nodes, respectively. Likewise, Monte Carlo simulation was implemented to conduct sensitivity analyses; "agent-based" and "game theoretic models" were also used for representing supply chain actors and their interests.

Next, the uncertainty inclusion is evaluated depending on the model: stochastic or deterministic. Finally, the decision-making levels were considered. The strategic level includes decisions regarding the production plant, biomass, markets and pretreatment plants. The tactical level includes the inventory and fleet decisions. The operational level has the decisions related to daily inventory and daily vehicle scheduling.

According to the assessment of the information in Table 4, it is clear that most of the studies reviewed do not consider daily vehicle scheduling. This occurs because most of the studies that develop daily vehicle scheduling only focus on this decision, and not on the whole BioRSC, which is a criteria for the present mapping study.

Among the publications that apply optimization, most developed the SC model using MILP, because of the binary nature of decisions. The majority of research has applied the ε-constraint method to solve optimization, but it has also used a genetic algorithm to solve multi-objective problems.

The main economic objective in the reviewed publications is profitability. And this has been sought by reducing costs, increasing revenues and maximizing the net present value. And only four investigations have considered the stochastic nature of the system in the models [54,76,102,123]. This shows that these models have not considered all the requirements for the design of the bio-based products' SC. There are only three investigations that have integrated optimization and pretreatments, Kim et al. [59] evaluate both centralized and decentralized SC network configurations and different biomass types. Bowling et al. [12] also consider distributed and centralized configurations and evaluate the possibility of selling biofuel sub-products. Gao [36] determines the location of the production plant by the BIOFLAME method prior to modeling and optimization, and then focus on the quantities of raw materials purchased and stored. The five studies focused on environmental objectives performed a lifecycle analysis to evaluate various impacts. Also, these publications do not consider market selection [32,45,83.113].

Among the researches focusing on economic and technological dimensions, only two have included pretreatment plants [57,64]. This is a very important aspect for biorefinery viability, because due to the low energy density of biomass and its dispersion, the harvest, logistic and transformation costs are penalized [62]. Thus, it is essential to consider the localization of pretreatment units to reduce transportation cost and optimize the supply of biomass to biorefineries [20].

There are two other publications that incorporate uncertainty in the model [4,109]. In regard to the studies with joint economic and social objectives, most propose deterministic models and none includes the pretreatment plants. In other, Bai et al. [6] considered the objective of maximizing net income for farmers and the biofuel industry, proposing a game theory based model, which includes decisions on land use, market selection by manufacturers and the impacts on raw material prices for the food industry. In this section, only Singh et al. [105] considered the stochastic nature of the problem, by applying MILP, a genetic algorithm and simulation based on agents. Another aspect concerns market competition, which is simulated, including biorefinery agents, farmers, and food market agents to determine the prices of raw materials that will be used in optimization.

75% of the documents target economic and environmental dimensions are deterministic, while only five have included pretreatment plants. Among them, there are those that have considered the environmental area as objective [92,99,129,130] and others that have considered the environmental aspect as restrictions for optimization.

Publications studying economic, environmental and technical dimensions of sustainability are fairly comprehensive regarding com-

Table 4
Publication analysis. (1) factory, (2) biomass, (3) market, (4) pre-treatments, (5) inventory, (6) fleet, (7) inventory, (8) fleet. Stochastic, St; deterministic, D; economic, Ec; social, So; Eenvironmental, En; political, Po; technological, Te; optimization O; simulation, S.

Publication	Objective	O/S	Specific tool	St/D	Decision-making level							
					Strategic				Tactical		Operational	
					(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
[30]	*Ec*	*O*	*MIP*	*D*	*X*	*X*			*X*	*X*	*X*	
[49]	*Ec*	*O*	*MILP*	*D*	*X*	*X*			*X*	*X*	*X*	
[59]	*Ec*	*O*	*MILP*	*D*	*X*	*X*	*X*	*X*		*X*	*X*	
[12]	*Ec*	*O*	*MILP*	*D*	*X*			*X*		*X*	*X*	
[36]	*Ec*	*O*	*MIP*	*D*				*X*	*X*	*X*		
[102]	*Ec*	*O*	*MILP*	*St*	*X*	*X*			*X*	*X*		
[46]	*Ec*	*O*	*MINLP*	*D*	*X*					*X*		
[54]	*Ec*	*O*	*SMILP*	*St*	*X*		*X*			*X*		
[68]	*Ec*	*O*	*MILP*	*D*	*X*	*X*			*X*	*X*		
[76]	*Ec*	*O*	*MILP*	*St*	*X*	*X*			*X*	*X*	*X*	
[27]	*Ec*	*O*	*MILP*	*D*	*X*	*X*	*X*		*X*	*X*	*X*	
[69]	*Ec*	*O*	*MILP*	*D*	*X*	*X*			*X*	*X*	*X*	*X*
[122]	*Ec*	*O*	*MILP + LP*	*D*	*X*	*X*	*X*		*X*	*X*	*X*	
[134]	*Ec*	*O*	*MINLP*	*D*	*X*	*X*	*X*			*X*	*X*	
[123]	*Ec*	*O*	*SMILP*	*St*	*X*	*X*			*X*		*X*	
[17]	*Ec*	*O*	*Mixed Integer Quadratically Constraint Programming (MIQCP)*	*D*	*X*	*X*						
[100]	*Ec*	*O*	*Mixed-Integer Dynamic Optimization*	*D*	*X*	*X*	*X*		*X*	*X*		
[106]	*Ec*	*S*	*EXTENDED tm*	*D*	*X*	*X*			*X*	*X*	*X*	
[88]	*Ec*	*S*	*Scenario analysis*	*D*	*X*	*X*			*X*	*X*	*X*	
[91]	*Ec*	*S*	*Scenario analysis*	*D*		*X*			*X*	*X*	*X*	
[73]	*Ec*	*S*	*Scenario analysis*	*St*	*X*	*X*	*X*		*X*	*X*	*X*	
[78]	*Ec*	*S*	*Scenario analysis*	*D*		*X*			*X*	*X*		
[57]	*Ec*	*O+S*	*MILP + Monte Carlo*	*St*	*X*	*X*	*X*	*X*		*X*		
[26]	*Ec*	*O+S*	*MILP + ASPEN*	*D*	*X*	*X*			*X*	*X*	*X*	
[56]	*Ec*	*O+S*	*MILP + HYSYS / Monte Carlo*	*St*	*X*	*X*					*X*	
[48]	*Ec*	*O+S*	*MILP + Montecarlo*	*St*	*X*							
[127]	*Ec*	*O+S*	*MINLP + Stackelberg game*	*St*	*X*	*X*	*X*					
[107]	*Ec*	*O+S*	*MILP + Aspen+ Discrete event simulation*	*St*	*X*	*X*				*X*		
[41]	*Ec*	*O+S*	*MILP, Scenario-based stochastic programming And Aspen Plus*	*S*	*X*	*X*	*X*				*X*	
[42]	*Ec*	*O+S*	*MILP + AspenPlus + Monte Carlo*	*St*	*X*	*X*					*X*	
[32]	*En*	*O*	*LP + LCA*	*D*	*X*	*X*		*X*	*X*	*X*		
[83]	*En*	*S*	*LCA + Monte Carlo*	*St*	*X*			*X*	*X*	*X*		
[45]	*En*	*S*	*LCA*	*D*	*X*	*X*		*X*		*X*		
[90]	*En*	*S*	*LCA*	*D*		*X*				*X*		
[113]	*En*	*O+S*	*MINLP + LCA*	*D*	*X*	*X*			*X*	*X*	*X*	
[28]	*Ec+Te*	*O*	*MILP*	*D*	*X*	*X*				*X*	*X*	
[89]	*Ec+Te*	*O*	*MILP*	*D*	*X*		*X*				*X*	
[110]	*Ec+Te*	*O*	*MIP*	*D*	*X*					*X*	*X*	
[58]	*Ec+Te*	*O*	*MILP*	*D*	*X*	*X*	*X*	*X*	*X*	*X*	*X*	
[31]	*Ec+Te*	*O*	*MILP*	*D*	*X*	*X*			*X*	*X*	*X*	
[75]	*Ec+Te*	*O*	*MILP*	*D*	*X*	*X*	*X*			*X*	*X*	
[103]	*Ec+Te*	*O*	*MILP*	*D*	*X*	*X*			*X*	*X*	*X*	
[4]	*Ec+Te*	*O*	*MILP*	*St*	*X*	*X*			*X*	*X*	*X*	
[86]	*Ec+Te*	*O*	*MILP*	*D*	*X*	*X*						
[95]	*Ec+Te*	*O+S*	*MILP + ASPEN*	*D*	*X*		*X*				*X*	
[66]	*Ec+Te*	*O+S*	*MILP + Steady-state simulation model*	*D*	*X*	*X*	*X*			*X*	*X*	
[108]	*Ec+Te*	*O+S*	*MILP + ASPEN*	*D*	*X*	*X*			*X*		*X*	
[109]	*Ec+Te*	*O+S*	*MILP + ASPEN*	*St*	*X*	*X*			*X*	*X*	*X*	
[64]	*Ec+Te*	*O+S*	*Biomass Logistics Model + Aspen*	*D*	*X*	*X*		*X*		*X*		
[6]	*Ec+So*	*O*	*MIQP*	*D*	*X*	*X*			*X*	*X*	*X*	
[60]	*Ec+So*	*O*	*MILP*	*D*	*X*	*X*				*X*		
[18]	*Ec+So*	*O+S*	*MINLP, MIP, MILP + Simulate behavior*	*D*	*X*	*X*				*X*	*X*	
[118]	*Ec+So*	*O+S*	*NLP + Game-theoretic models*	*D*	*X*	*X*				*X*	*X*	
[105]	*Ec+So*	*O+S*	*MILP (Genetic algorithm) + AGENT-BASED*	*St*	*X*	*X*	*X*		*X*	*X*	*X*	
[129]	*Ec+En*	*O*	*MO MILP*	*D*	*X*	*X*	*X*			*X*	*X*	
[130]	*Ec+En*	*O*	*MO MILP*	*D*	*X*	*X*	*X*			*X*	*X*	
[98]	*Ec+En*	*O*	*MILP*	*St*	*X*	*X*	*X*		*X*	*X*		
[92]	*Ec+En*	*O*	*MO NLP*	*D*	*X*	*X*				*X*	*X*	
[81]	*Ec+En*	*O*	*MO MILP*	*D*	*X*	*X*	*X*	*X*		*X*		
[25]	*Ec+En*	*O*	*MILP*	*D*	*X*	*X*	*X*	*X*				
[117]	*Ec+En*	*O+S*	*MILP + LCA + Aspen*	*D*	*X*	*X*				*X*		
[61]	*Ec+En*	*O+S*	*MILP + Aspen + Sensitivity analysis*	*St*	*X*	*X*	*X*		*X*	*X*		
[132]	*Ec+En*	*O+S*	*MILP + ASPEN*	*D*	*X*	*X*		*X*	*X*	*X*	*X*	
[94]	*Ec+En*	*O+S*	*MILP + ASPEN*	*D*	*X*		*X*				*X*	
[97]	*Ec+En*	*O+S*	*MO + Monte Carlo*	*St*	*X*	*X*	*X*	*X*	*X*	*X*		
[131]	*Ec+En*	*S*	*ARENA + IDEF*	*D*		*X*		*X*	*X*	*X*	*X*	
[77]	*En+Te*	*S*	*LCA*	*D*	*X*	*X*		*X*				
[39]	*Ec+Po+Te*	*O*	*SMILP*	*St*	*X*				*X*	*X*	*X*	
[40]	*Ec+Po+Te*	*O*	*SMILP*	*St*	*X*				*X*	*X*	*X*	

(continued on next page)

Table 4 *(continued)*

Publication	Objective	O/S	Specific tool	St/D	Decision-making level							
					Strategic				Tactical		Operational	
					(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
[2]	Ec+So+Te	O	MILP	D	X	X			X	X	X	
[99]	Ec+En+Te	O	MO MILP	D	X	X	X	X		X	X	
[70]	Ec+En+Te	O	MILP	D	X	X	X	X	X	X	X	
[87]	Ec+En+Te	O	MILP	St	X		X		X	X	X	
[15]	Ec+En+Te	O	MIP	D	X	X						
[63]	Ec+En+Te	O+S	MILP+ Sensitivity analysis	St		X		X		X		
[79]	Ec+En+So	O	MILP	D	X	X			X	X		
[74]	Ec+En+So	O	MILP + Scenario analysis	D	X	X				X		
[133]	Ec+En+So	O	Genetic algorithm	St	X	X		X				
[74]	Ec+En+So	O + S	MILP and scenarios	D	X	X						
[96]	Ec+En+So+Te	O	MILP	D	X	X	X	X	X	X	X	
[7]	Ec+En+So+Te	O	MILP, Multiobjective robust possibilistic programming (MORPP) approach is developed	St	X	X	X	X	X	X		
[14]	Ec+En+So+Te	O	MILP	D	X	X	X					
[125]	Ec+En+Po+Te	O	MILP	D	X	X				X	X	
[126]	Ec+So+En+Po +Te	O	MO MILF	D	X	X		X	X	X	X	
[124]	Ec+So+En+Po +Te	O+S	MO MILP+ASPEN	D	X	X		X	X	X	X	

prised decisions. Santibañez-Aguilar et al. [99] propose a general superstructure and a mathematical programming model for the sustainable elimination of water hyacinth through a distributed biorefinery network, considering economic and environmental objectives and several technologies available. Osmani and Zhang [87] present a two-stage stochastic optimization model to maximize the expected profit and simultaneously minimize carbon emissions. But they assume that the demand for co-products is always greater than supply. Liu et al. [70] use a model with multi-conversion pathways and propose a framework for economic, energy and environmental performance measures. Finally, Lamers et al. [63] made an evaluation limited to a subset of potential depot designs, without including the upstream or downstream supply chain.

The two studies that take into consideration the five dimensions of sustainability are You et al. [124] and Yue et al. [126]. The first uses ASPEN to simulate different possible production lines to choose the production technology and includes government incentives as incomes. Its objective is to minimize the annualized costs, maximize local job creation and minimize greenhouse gas emissions. On the other hand, Yue et al. [126] evaluate the cost of producing electricity, the number of local jobs created and the environmental impacts associated with the production of a unit of bioelectricity, by LCA methodology. It also considers government subsidies as income for the biorefinery. In both studies only one production technology per plant could be chosen and no consideration is given to economies of scale in the technological dimension of sustainability. None of these last studies evaluates the target market selection.

To finish, most of the recent researches published develops the sustainability analysis in a traditional way, using economic, environmental and social dimensions, as reported in other references without considering the inclusion of variables such as economies of scale or incentives provided by governments or the integration of assessment of "developing technologies" with different maturity levels [5,38,43,65].

Moreover, as a general rule, analyzed researches focus mainly on one principal final product, such as biofuel, but biorefineries' higher added value products and energy integration can further support the sustainability balance [9]. Therefore they must also be considered.

5. Discussion

Although the study of BioRSC started several years ago, almost parallel to sustainability studies based on three axes (social, economic and environmental), sustainability based on three axes was fully integrated in only six of the studies reviewed. When considering the new sustainability approach based on five axes, there are only two studies that consider all aspects. The few investigations that included the political dimension have considered government incentives as a profitability source for the enterprise, leaving behind the political objective of reducing economic incentives when the industry would be self-sustaining. Therefore, it is necessary to consider these two sides of the political dimension of sustainability.

Regarding the application of the technological dimension of sustainability, even though it has been considered in 36% of the publications, the vast majority has only evaluated the choice of production technologies, without assessing technological learning, economies of scale or the development of new technologies. These are issues that could help improve the profitability of enterprises, encouraging more private investment in the field.

Some of the researchers take into account the nature of the biomass, but only 29% have incorporated uncertainty in their studies. In addition, among the last nine publications in Table 4, the most relevant studies related to sustainability, only three of them have considered the target market selection for the different biorefinery final products and sub-products. This means that the integration of high value products has simply been ignored. Incorporating this decision can represent an opportunity to improve economic performance, since profitability is a fundamental pillar for BioRSC industrialization.

These results show that none of the publications targeted system complexity as a whole. From the above evidence, it could be concluded that the Biorefinery Supply Chain (BioRSC) is still studied in a fragmented and partial manner. Due to the growing importance of this sector, it is necessary to implement integrated frameworks and operational tools that support the decision-making process.

To conclude, the main findings of this mapping study are included in Table 5, as the "Current Status" of the BioRSC study and the "Ideal System Model." The latter presents the characteristics needed for a decision-making support tool that facilitates the sustainable industrialization of BiorSC.

6. Conclusion

Biorefineries are an opportunity to use natural resources in a sustainable way. BioRSC design and management for sustainable industrialization must integrate the requirements and constraints

Table 5
Main findings summary.

	Current Status	*Ideal System Model*
Sustainability: inclusion of the five dimensions	Early stage for simple systems	Full integration of the five dimensions and scenarios considered
Comprehension	Partial vision approaches	Full integration of stakeholders and the three decision-making levels
Complexity / Completeness	Simple systems, i.e. biodiesel	Integrated biorefinery, with high added value products and pretreatment plants
Modeling and optimization approaches	Use separately: – Sensitivity analysis – Simulate behavior – Multi-Objective optimization – Mixed Integer Linear Programming – Simulation by ASPEN	Integration of tools for robust optimization and behavior comprehension.

linked to nature, sustainability and the decision-making levels described in this section.

Even though the decision-making support tools for BioRSC have evolved from first applications, a tool that facilitates sustainable biorefinery implementation has not yet been developed. This tool would need to incorporate uncertainty, the different decisions for the decision-making levels and the five dimensions of sustainability to cover the requirements that have not been met.

This research lays the basis for the design of a decision-making support tool that facilitates the sustainable industrialization of BiorSC. Nevertheless, since in the present study only the publications related to the whole BioRSC are considered, another study can be conducted to analyze the research in more detail and then perform the integration of these models for designing the decision-making supporting tool required.

Finally, the approach to be proposed in future for the design tool is to develop a model for the biorefinery supply chain system that measures only one sustainability dimension. A more realistic model should be elaborated by integrating the decision-making variables of one decision level and the requirements and constraints linked to the nature of the biorefinery. Once this model is validated, it can be much easier to integrate the other sustainability dimensions and the tactical and operational decision-making levels.

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