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Review

Impact of Product Diversification on the Economic Sustainability of Second-Generation Ethanol Biorefineries: A Critical Review

Vinícius P. Shibukawa [1], Lucas Ramos [1], Mónica M. Cruz-Santos [1], Carina A. Prado [1], Fanny M. Jofre [1], Gabriel L. de Arruda [1], Silvio S. da Silva [1], Solange I. Mussatto [2,*] and Júlio C. dos Santos [1]

[1] Department of Biotechnology, School of Engineering of Lorena, University of São Paulo, Estrada Municipal do Campinho, Lorena 12602810, SP, Brazil; vinicius.ps@usp.br (V.P.S.); lucas.eng12@gmail.com (L.R.); monica.csantos@usp.br (M.M.C.-S.); carinaprado@usp.br (C.A.P.); jofrefanny@usp.br (F.M.J.); gabrielleda@usp.br (G.L.d.A.); silviosilverio@usp.br (S.S.d.S.); jsant200@usp.br (J.C.d.S.)

[2] Department of Biotechnology and Biomedicine, Technical University of Denmark, Søltofts Plads, Building 223, 2800 Kongens Lyngby, Denmark

* Correspondence: smussatto@dtu.dk or solangemussatto@hotmail.com

Abstract: The replacement of fossil-based products with renewable alternatives is today a major research topic. Biofuels, such as second-generation ethanol, offer a promising way to overcome dependence on fossil fuels. However, second-generation biorefineries still face bottlenecks that hinder their economic sustainability. These include challenges in pretreatment (formation of inhibitors and high costs of chemicals) and hydrolysis (high enzyme costs and low solid content) and maximizing the utilization of biomass components. To achieve economic sustainability, biorefineries can adopt approaches such as integrating first and second generation (1G and 2G) technologies, using different production alternatives, or diversifying the product portfolio. This last alternative could include the simultaneous production of biomaterials, building blocks, and others from all fractions of the materials, favoring biorefinery profitability. Techno-economic assessment plays a crucial role in assessing the economic feasibility of these approaches and provides important information about the process. This article discusses how product diversification in cellulosic biorefineries enhances their economic sustainability, based on simulation techniques and techno-economic analysis, with a comprehensive and critical review of current possibilities and future trends. The information discussed can inform stakeholders about investing in 2G ethanol biorefineries, including strategies, associated risks, and profitability, allowing better planning of different options of future ventures.

Keywords: 2G ethanol; biorefineries; techno-economic assessment

Citation: Shibukawa, V.P.; Ramos, L.; Cruz-Santos, M.M.; Prado, C.A.; Jofre, F.M.; de Arruda, G.L.; da Silva, S.S.; Mussatto, S.I.; dos Santos, J.C. Impact of Product Diversification on the Economic Sustainability of Second-Generation Ethanol Biorefineries: A Critical Review. *Energies* **2023**, *16*, 6384. https://doi.org/10.3390/en16176384

Academic Editor: Idiano D'Adamo

Received: 31 July 2023
Revised: 30 August 2023
Accepted: 30 August 2023
Published: 3 September 2023

1. Introduction

In a world of increasing human and technological development, the demand for new energy sources is growing at an accelerated pace. This is driven by the need to diversify the energy mix to ensure a stable supply for the population and reduce dependence on fossil fuels. The decrease in fossil fuel reserves, geopolitical influences, and the negative environmental implications associated with their use further emphasize the urgency for alternative options [1,2]. If the human population continues to grow at its current rate, projections suggest that by 2050, the global population will reach 9.4 billion people [3]. This rapid growth is anticipated to lead to increased demands for both energy and food resources. In this context, biomass, particularly lignocellulosic biomass, has gained significant prominence worldwide. It is valued for its widespread geographical distribution, abundance, and potential for utilization [4].

The availability of lignocellulosic biomass is closely tied to continuous advancements in agriculture, livestock, forest, and agro-industries, which generate a significant volume of waste [5]. Utilizing lignocellulosic biomass as an energy source aligns with the concept of carbon fixation. It naturally occurs through the absorption of carbon dioxide from the atmosphere by plants during their growth and development. Consequently, plant biomass, particularly forest and agro-industrial residues and by-products, can be classified as a renewable and environmentally friendly matrix for energy production [6]. This has stimulated a noteworthy market for the trading of carbon credits, incentivizing countries to adopt fewer polluting technologies and promote the use of plant biomass as an energy source [7]. As highlighted by D'adamo et al. [4], the utilization of biomass for energy production aligns with the United Nations' Global Development Goals. This offers a substantial opportunity to enhance energy generation through biomass resources, a prospect that is particularly noteworthy given its high impact when compared to other renewable sources. One of the notable advantages of this approach is its ability to sidestep competition with the food supply chain, rendering it a sustainable avenue for energy production. Additionally, biomass stands out as a non-intensive greenhouse gas emission energy source, further accentuating its environmental advantages.

Lignocellulosic biomass primarily consists of three main fractions: cellulose, hemicellulose, and lignin. Cellulose, the predominant fraction in the lignocellulosic materials, is composed of glucose units linked by β-1-4 bonds [8,9]. The hemicellulose fraction, on the other hand, is an amorphous and heterogeneous polymeric fraction. It comprises sugars, such as xylose, arabinose, mannose, and glucose, as well as acid groups like acetic and glucuronic acid [10]. In contrast, the lignin fraction is a highly complex and aromatic macromolecule. It consists of phenyl propane structural units and various groups, creating a matrix that strongly binds with the cellulose and hemicellulose structures [11,12]. Despite its rich composition, lignocellulosic biomass, whether of residual origin or generated as by-products, is primarily used for energy generation through material combustion. This includes processes such as charcoal production, steam and heat generation, and complete combustion in boilers. As a result, they represent a significant portion of global energy generation [13].

Lignocellulosic biomass derived from agricultural and industrial activities is still undervalued despite its widespread availability. This is especially true for fast-growing grasses of commercial importance, such as sugarcane, corn, wheat, barley, rice, and fruit residues. Additionally, a significant portion of forest residues also remains in the field due to the lack of profitable utilization processes [14,15]. However, the primary challenge in processing lignocellulosic biomass lies in achieving a complete separation of its carbohydrate and polymer fractions, which are inherently interconnected within the biomass structure. These fractions are naturally designed to provide rigidity, strength, and protection to the plant cell wall [9].

Despite the various processes available today for the fractionation of lignocellulosic biomass, such as acidic [16], alkaline [17], thermal [18], or enzymatic [14], the efficient obtainment of monosaccharides to produce 2G ethanol and other biomolecules remains a challenge at the industrial level. One potential approach is to leverage existing well-established industrial facilities and adapt the processes based on the type and availability of biomass required for the desired product. In this regard, the development of biorefineries can play a crucial role in the more efficient utilization of lignocellulosic biomass. Biorefineries can enable the cogeneration of energy and the production of fuels and other valuable products using lignocellulosic biomass.

Evolved from the concept of oil refineries, which extract multiple products from a single raw material (crude oil), biorefineries focus on "refining biomass". This refining process can be integrated into existing technological pathways, such as the pulp and paper, sugar-energy, and starch conversion industries [19]. In its current conceptualization, a biorefinery represents a multi-product production process. It allows for greater flexibility in the production chains of established industrial plants, as it values the raw material, its residues, and the by-products generated during the process. By implementing various technologies, biorefineries aim to obtain a broader range of products from biomass, thereby expanding their product portfolios [19–21].

Currently, a significant portion of research and technological development efforts in the field of biorefineries are primarily focused on energy generation. This includes the production of biofuels, such as 2G ethanol, biodiesel, and biogas, as well as the direct combustion of biomass to generate steam and electricity [22]. Of particular importance is the production and co-production of 2G ethanol, which capitalizes on existing industrial infrastructure combined with the availability of raw materials, specifically lignocellulosic biomass. This biomass can be derived from the production of 1G ethanol or obtained as a by-product from other processes. Notable examples include the production of 2G ethanol from sugarcane bagasse (SCB) in Brazil and China, agricultural residues from corn in the USA, and wheat and barley residues in Europe. Furthermore, forestry resources in Russia as well as the abundant agro-industrial residues in China and India contribute significantly to the quantity and availability of biomass for ethanol and energy production [6,15,23].

Investing in the production of 2G ethanol derived from lignocellulosic biomass represents a significant step towards reducing dependence on fossil fuels. Currently, a substantial portion of ethanol production worldwide is allocated for use as automotive fuel, either in its pure form or as an additive in petroleum-based fuels, particularly gasoline. However, most of the ethanol used for this purpose is still derived from sugarcane or starch, falling under the category of 1G ethanol [24].

Another crucial strategy to enhance and optimize the production processes of 2G ethanol is the integration of techno-economic assessment (TEA) tools with novel approaches for pretreatment and hydrolysis of lignocellulosic biomass. These strategies can significantly contribute to the feasibility and efficiency of production processes, both in existing industrial operations and those in the implementation stage [25,26].

A TEA is often conducted in conjunction with process simulation studies, as they complement each other. Process simulation studies provide valuable information about mass and energy balances, identify potential bottlenecks, explore process integration opportunities, and more. Based on the data obtained from process simulations, a TEA is then performed to assess the economic sustainability of units [27,28].

Both process simulation studies and the TEA are typically supported by specialized software tools, such as Aspen Plus, SuperPro Designer, and others. These studies can be conducted within a single software platform or using separate software tools depending on the specific needs and preferences of the researchers [28].

The TEA plays a crucial role in evaluating the economic feasibility of a process, technology, or product and provides valuable insights for potential investors [28]. In the case of 2G ethanol, its economic sustainability is still a challenge due to known bottlenecks that negatively impact economic parameters. Some of these challenges include the pretreatment process [29], high enzyme costs [30], and the allocation of the pentose biomass fraction [31]. However, researchers are actively working to overcome these issues through various studies. For instance, new pretreatment techniques are being explored to improve process efficiency and reduce costs [32]. Additionally, advancements in the allocation of the pentose biomass fraction are being investigated to maximize the revenues of a biorefinery [30].

By conducting a TEA and exploring alternative approaches, researchers aim to address these challenges and enhance the economic viability of 2G ethanol production. These efforts are critical for attracting investments and establishing a sustainable business model for the industry [28].

One approach to address the economic challenges of 2G ethanol production is through product diversification within the biorefinery. By valorizing side-streams that contain carbohydrates (hemicellulose) or high-value macromolecules (lignin), additional revenue can be generated, thereby increasing the overall profitability of the biorefinery. Other biofuels and products, such as furfural [33,34], biogas [35], biodiesel [36,37], biochar [38], carotenoids [39], and others, have been reported as alternatives to be produced together with 2G ethanol. In this review, studies that have focused on product diversification to enhance the economic sustainability of 2G ethanol biorefineries are discussed, highlighting those that are utilizing both process simulation studies and a TEA. Currently, there is a gap regarding recent review articles that comprehensively discuss the economic sustainability of second-generation (2G) ethanol biorefineries focused on the context of product portfolio diversification. This kind of discussion is fundamental and can direct efforts and allocation of valuable resources towards potentially promising approaches that may not have been considered due to the absence of consolidated data on this topic. Existing research articles primarily focus on the exploration of one to three bioproducts alongside 2G ethanol production. This review addresses this gap by presenting a comprehensive overview of potentially promising bioproducts that have been the subject of portfolio diversification through a techno-economic assessment. Moreover, the review sheds light on additional products that hold the potential for integration with ethanol production, further emphasizing the significance of this unexplored area in the field of biorefineries.

2. Lignocellulosic Biomass, Processing, and Applications: A Highlight on Second-Generation Ethanol

Approximately 180 billion tons of lignocellulosic biomass are produced worldwide, with the main components being forest and industrial residues and associated by-products [40]. Given its abundant availability, numerous studies have emerged with the aim of harnessing the various types of lignocellulosic biomass. These efforts seek to capitalize on the vast potential of this resource by exploring innovative applications and developing sustainable solutions. Recent research has been active in investigating methods to optimize the utilization of lignocellulosic biomass, striving to unlock its inherent value and contribute to the advancement of renewable energy, bio-based products, and environmental conservation [41].

The main reason why lignocellulosic biomass is attractive is because of its composition, including mostly cellulose (35–60%), hemicellulose (20–35%), and lignin (10–25%) fractions, along with small amounts of water and ash [42]. The content of lignocellulosic material in biomass depends on the specific type of biomass and its origin [43,44]. Lignocellulosic biomass can be classified into several categories, including hardwood, softwood, food and non-food, agro-industrial residues, grasses, and weeds. Within this classification, different types of products, such as leaves, shells, stems, and bark, among others, can be found [44].

However, the industrial use of lignocellulosic biomass poses significant challenges due to its recalcitrance, resulting from its closed structure. Nonetheless, substantial progress has been made in developing saccharification methods aimed at obtaining sugars on biorefinery applications. In the current developing biorefineries aimed at 2G ethanol production, enzymatic hydrolysis of carbohydrate fractions has been used, but the digestibility of biomass by enzymes must be previously increased by a pretreatment method.

The pretreatment of the raw material plays a crucial role in enabling the utilization of various fractions of cellulosic biomass, as it directly impacts the yield of subsequent steps and is one of the costliest processes involved [45]. An optimal pretreatment method should have low capital and operating costs, demonstrate effectiveness across a wide range of biomass types, achieve high yields, and allow for the utilization of as many fractions as possible from the treated material while minimizing waste [9,46].

The objective of pretreatment is to alter the lignocellulosic structure, increasing the biomass's surface area and porosity by partially removing the lignin fraction. This process helps reduce the recalcitrance of the biomass and improves the accessibility of cellulose by reducing cellulose crystallinity [9,46]. Pretreatment is typically categorized as mechanical, chemical, physicochemical, and biological [47]. However, it is important to note that pretreatments, in addition to increasing the enzymatic digestibility of the biomass, should also have minimal impact in terms of cost and environmental considerations.

Following pretreatment, the biomass undergoes enzymatic hydrolysis, which is essential to produce fermentable sugars, including both C6 and C5 sugars [48]. Enzyme complexes containing betaglucosidase, endoglucanases, exoglucanases, xylanases, and other enzymes act on the carbohydrates, breaking them down into their monomeric fractions. Cellulose is converted to glucose and hemicellulose, which are primarily composed of xylose in the case of biomasses such as SCB, which is converted to xylose as well. This step is crucial since many microorganisms can assimilate monomeric sugars but not the polymeric form [49,50]. However, this step remains a bottleneck due to the high costs of enzyme complexes and low solid content in the reactor, for example [30,51].

After enzymatic hydrolysis, a sugar-rich stream is obtained and directed to the fermentation section. Microorganisms, such as yeast, bacteria, or fungi, assimilate these sugars, resulting in the production of bioproducts of interest. Hydrolysis and fermentation can be combined or completed separately, and it is also possible, depending on the microorganism used, to co-ferment C5 together with C6 fractions. Diverse process configurations are available, including separated hydrolysis and fermentation (SSF), simultaneous saccharification and fermentation (SSF), separated hydrolysis and co-fermentation (SHCF), and simultaneous saccharification and co-fermentation (SSCF) [50,52].

Furthermore, it is also possible to accomplish pretreatment, hydrolysis, and fermentation in just one reactor, a process known as a consolidated bioprocess (CBP). In a CBP, biomass pretreatment, enzyme production, enzymatic hydrolysis, and fermentation occur simultaneously [53].

The alternatives of processing of biomass must be defined considering the possible chemicals and fuels to be obtained. Indeed, lignocellulosics can be used in biorefineries as a sustainable and renewable carbon source to produce a great variety of interesting chemicals and fuels [54,55].

One example of an important product from lignocellulosic biomass includes xylitol, which is one of the most studied compounds obtained from hemicellulose, with an interesting possibility of replacement of the conventional chemical process by a biotechnology [56]. As other examples, Terán-Hilares et al. [57] produced *Monascus ruber* red biopigments from SCB hydrolysate, and Cruz-Santos et al. [58] conducted an extensive investigation of the production of pullulan, an industrially important biopolymer, from different lignocellulosic biomasses. However, the main product studied and obtained from lignocellulosic biomass is second-generation ethanol (2G).

Second-generation ethanol, also known as bioethanol, green ethanol, or cellulosic ethanol, is recognized for having one of the lowest carbon footprints among fuels worldwide [59,60].

In terms of 1G ethanol production, Brazil ranks as the second-largest producer globally, following the United States, which primarily uses corn as the raw material in the production process. Due to fluctuations in biofuel prices and the seasonality of sugarcane, Brazilian producers are also exploring the use of corn in some plants [61]. Nowadays, Brazil already has nine operating corn ethanol plants, with most of them located in the Midwest region. These plants are called flex plants since they can utilize both biomass, sugarcane, and corn—this is a good solution to reduce the idleness of the facilities. Additionally, there are 15 more corn ethanol plants under construction or in the licensing process. This expansion is seen as a solution to meet market demand and to help handling corn production in the Midwest Brazilian region [62–64].

Regarding second-generation ethanol, ongoing research efforts are focused on improving the efficiency of the process. One key area of interest is the use of all carbohydrate fractions of the material, thus including the hemicellulose. The hydrolysis of hemicellulose in second-generation ethanol production can occur either during the pretreatment step or together with glucose in the enzymatic hydrolysis step. This hydrolysis primarily results in the formation of C5 monomers. To utilize these pentose sugars in the fermentation process, genetically modified microorganisms or specific yeasts capable of fermenting pentoses, such as *Schefersomyces stipitis* and *Candida shehatae*, are employed [65,66]. However, the utilization of pentoses in fermentation remains a challenge, with research efforts focused on overcoming this technological bottleneck and realizing the economic feasibility of their utilization [29,67].

Currently, Brazil has one operational second-generation (2G) ethanol plant, operated by Raízen, while five additional plants are under construction. The operational plant, inaugurated in 2014, has achieved a significant milestone by producing 30 million liters of 2G ethanol during the 2022/23 harvest season. Each of the five plants under construction is designed with a production capacity of 82 million liters and an estimated capital expenditure (Capex) of BRL 1.2 billion. The outlook for the 2G ethanol industry in Brazil is optimistic, with expectations that at least 20 operational 2G ethanol plants will be established by 2030 [63].

Considering the USA's 2G ethanol production, one example of a biorefinery that uses corn cobs is POET Biorefining, a leading ethanol producer in the United States. They have several facilities that utilize corn cobs as a feedstock alongside corn grain. The corn cobs are processed to extract valuable components, such as cellulose and hemicellulose, which can be converted into ethanol or other bio-based products [68,69].

Other biofuels can also be produced from lignocellulosic biomass, including biomethane, bioethane, and biohydrogen. Akbarian et al. [70] have highlighted that the process of biogasification enables the attainment of sustainability objectives, leading to a decrease in the production and consumption of fossil fuels and subsequently mitigating environmental impacts. This utilization of lignocellulosic biomass for biogas production not only fosters an eco-friendlier approach but also contributes to the overall diversification and advancement of renewable energy sources [71]. In addition, the production of biohydrogen is currently positioned as a usable energy alternative with less generation of pollutants [72].

Other products that can be produced from lignocellulosic biomass are biopesticides [73], biobutanol [74], volatile fatty acids [75], enzymes [76], and other valuable products, as observed in Table 1.

Therefore, lignocellulosic biomass from agro-industrial processes can be converted to obtain products other than 2G ethanol, such as pigments, animal feed, and electricity. The ethanol 2G biorefinery can be integrated with these different processes and thus increase its economic viability. This diversification of vegetal biomass favors its valorization in the context of biorefineries and the circular bioeconomy.

However, for any possible sustainable biorefinery, economic aspects must be considered. Sustainability is a tripod [101], and all its aspects, i.e., social, environmental, and economic, are fundamental to any available or upcoming biorefinery.

Table 1. Literature examples of interesting products which can be included in a biorefinery from lignocellulosic biomass.

Lignocellulosic Biomass	Composition			Products in Biorefinery	References
	Cellulose	Hemicellulose	Lignin		
Agro-industrial residues and by-products					
Wheat straw	39.0	23.1–29	16–22.3	Bioethanol, biohydrogen, biogas	Geng et al. [77]; Kaparaju et al. [78]
Sugarcane bagasse	40.01–42.3	24.4–27.60	20.5–26.26	Pullulan, biopigments, bioethanol	Geng et al. [77]; Terán-Hilares et al. [79]; Terán-Hilares et al. [57]; Terán-Hilares et al. [80]
Rice straw	37–43.48	24–28.13	3.29–14	Biopigments, volatile fatty acids, bioethanol, biopolymers	Liu et al. [81]; Eraky et al. [75]; Kaur et al. [82]
Rice husk	25–35	18–21	26–31	Bioethanol, biopesticide, biopigments, polyesters	Zhang et al. [83]; Sehgal et al. [73]
Corn cob	29–45	27–39	14–18	Xylitol, ethanol, biohydrogen	Du et at. [84]; Kucharska et al. [85]
Corn stover	31.9–38.42	16.7–30.6	13–21.0	Bioethanol, biobutanol	Aghaei et al. [86]; Hijosa-Valsero et al. [87]
Hazelnut shell	24–28	28–29	34–42	Ethanol, pullulan, enzymes	Uyan et al. [74]; Akdeniz-Oktay et al. [88]; Ozzeybek, M.; and Cekmecelioglu [76]
Cotton stalk	33–36	9–18	25–31	Bioethanol, biomethane, biohydrogen	Keshav et al. [89]; Sołowski et al. [90]
Apple pomace	7–44	4–24	15–23	Biogas, ethanol, mycoprotein, enzymes, beer flavoring, pullulan	Borujeni et al. [91]; Singh et al. [92]; Ricci et al. [93]; Akdeniz-Oktay et al. [88]
Hardwood					
Eucalypt	43.2–44.4	15.2–16.8	24.5–27.5	Bioethanol, biomethanol	Cebreiros et al. [94]; Geng et al. [77]
Beech	36.79	37.79	22.81	Acetone, ethanol	Asada et al. [95];
Maple	43.2	17.1	25.2	-	Geng et al. [77]
Softwood					
Cedar	37.99	26.64	32–33.41	Flavorful alcohols	Asada et al. [95]
Spruce chips	43–45.5	20.6–21.3	26.9–30.1	Yeast biomass, butanol	Lapeña et al. [96]; Caputo et al. [97]; Yang et al. [98]
Grasses					
Switchgrass	35.5	26.4	23.2		Geng et al. [77]
Arundo donax; Phragmites communis (*Cav.*); *Trin. ex Steud; Pennisetum purpureum Schum.; Saccharum arundinaceum Retz.; Panicum virgatum* L.	22.2–33.7	26.8–32.2	10.1–22.4	Biohydrogen	Zhang et al. [99]
Bamboo	38–51	20–29	21–31	Biogas	Liakakou et al. [100]

3. Process Simulation and Techno-Economic Assessment Studies

Process simulation is a valuable resource for projecting, replicating, or modifying the behavior of a process to gain insight into its operation and integration. It is conducted by the utilization of mathematical equations that model the process being simulated. Process simulation serves as an experimental in silico approach to understand how a process functions and its unique characteristics [27]. These tools are interesting because they can enhance our understanding of how one operation within the process affects others. They can estimate the impact on the result if changes are made, perform mass and energy balances, propose optimization procedures, and conduct tests that greatly aid in process analysis without the need for extensive experimental work [102–104].

Over the years, process simulation tools have gained immense popularity due to their compatibility with various computer setups. Currently, there is a wide array of process simulation software available, such as Aspen Plus, Aspen Hysys, Prosim, SuperPro Designer, and others [105]. For instance, Aspen Plus is well suited for petroleum industries, while SuperPro Designer was developed for pharmaceutical industries. However, it is important to note that the chemical and biochemical sectors are only one example of the numerous domains where simulation can be applied. Nunes [106] for example, utilized geoprocessing data to develop a simulation scenario for guiding mining activities, while Liu et al. [107] employed numerical simulations to investigate the impact of microstructure and its evolution in metal cutting processes.

As can be observed, simulation software is employed across various industries, highlighting the growing significance of these tools in today's world. Aided by them, one important type of study that can be carried out is sensitivity analysis. This powerful technique aids in comprehending the impact and sensitivity of an independent parameter on a dependent parameter. Sensitivity analysis assists in identifying the most influential parameters within a process, allowing for a better understanding of their overall influence. Consequently, this information can help in determining the key parameters that shape the entire process [108].

For instance, Salman et al. [108] conducted a comparative study between a conventional natural gas dehydration method and a stripping gas method. They performed a sensitivity analysis on several parameters to determine the optimal conditions. The results led the authors to conclude that the stripping gas method is better suited for the process. The sensitivity analysis revealed that the water content of the dry gas was the most influential parameter on the raw material's feed rate. Decreasing the raw material's feed rate resulted in lower reboiler duty and reduced raw material losses [108].

Another important analysis for engineers, widely employed nowadays, is the TEA of the processes. The utilization of simulation software to assist in the TEA is crucial as these tools provide information regarding mass and energy balances, potential bottlenecks, and aid in evaluating equipment sizing for the installation. The TEA plays a significant role in assessing the economic viability of a facility, determining entrepreneurial risks, and enabling stakeholders and potential investors to make informed decisions regarding future investments [28,35]. Typically, the TEA incorporates parameters such as capital expenditure (CAPEX), operational expenditure (OPEX), payback period, internal rate of return, minimum selling price (MSP), and other economic indicators that are instrumental in comparing different scenarios and identifying process bottlenecks [109,110]. TEA studies conducted for technologies in the early stages of development are essential to ensure their competitiveness against existing options and to attract investment interest, thereby facilitating the advancement of the technology [111].

In the work conducted by Ianda et al. [112], the TEA compared the minimum selling price of microalgae biodiesel (USD 0.9/kg) with that of commercial diesel. Based on this analysis, the authors concluded that microalgae biodiesel shows promising competitiveness. Another notable aspect of the study by Ianda et al. [112] was the consideration of the Guinea-Bissau scenario. This aspect highlights the importance of considering specific country conditions, as different countries may have varying economic parameters.

Unfortunately, this variability sometimes makes it challenging to compare TEA studies that involve different case scenarios. To address this issue, some authors, such as Zimmermann et al. [113], have developed systematic guidelines for conducting a TEA of carbon capture and utilization. These guidelines facilitate comparisons between different technologies and applications by establishing a framework for scenario analysis, including considerations of technological maturity, system boundaries, and identification of benchmark systems [113].

Exactly like process simulation, TEA studies do not encompass just chemical and biochemical cases. For example, Oughton and Lehr (2022) [114] completed a TEA over the new technology for sixth cellular generation wireless networks to understand the current state-of-the-art for wireless networks and help address insights for its development. Another case study that completed a TEA is presented in Veilleux et al. [115], which studies a redesign and refinance of a rural electrical microgrid in an island in Thailand. Authors studied several scenarios and demonstrated the feasibility of economic return for investors to attract attention for initiatives or public policy makers to accelerate this kind of initiative in Southeast Asia. A TEA not only directs investors and stakeholders to make revenues; it can also be used to show that investing in a determined area can bring revenues while enhance the quality of life of the local population.

Another analysis that can be completed utilizing data from simulation software is a life cycle assessment (LCA), which estimates the environmental impact associated with a product throughout its lifetime. An LCA typically considers various stages, including raw material extraction, processing, manufacturing, distribution, and utilization. However, it is crucial to define the system boundaries for this type of analysis. There are different LCA approaches: cradle-to-grave LCA encompasses the entire life cycle from the manufacturing stage to the disposal phase; cradle-to-gate LCA covers the life cycle up to the factory gate, excluding transportation to the consumer; and cradle-to-cradle LCA is like cradle-to-grave, but includes a recycling process in the disposal stage [116]. In certain studies, particularly in review articles, it is common practice to combine a TEA with an LCA to evaluate the sustainability, both in terms of environmental and economic aspects, of the facilities or products under investigation. These studies often focus on biofuels and renewable energy. However, it is currently typical in original research articles to perform a TEA and LCA separately. Nevertheless, there is a growing recognition of the benefits of systematically integrating these two types of analyses, as it can facilitate decision making from both an environmental and an economic perspective [104]. In spite of this, the present review article specifically focused on the TEA of cellulosic ethanol, considering that its economic sustainability is yet to be proven and most of the processes studied to date still require improvements to achieve desirable revenue for their facilities [117].

Tecno-Economic Analysis of 2G Ethanol Biorefineries

Second-generation ethanol biorefineries have been the subject of extensive study for a considerable period. However, to this day, there remain bottlenecks that hinder their economic sustainability [117]. For instance, biomass pretreatment [29,31], enzyme costs [30,118], and the destination of the pentose biomass fraction pose significant challenges for scientists. Aui et al. [117] completed a meta-analysis of the techno-economic studies on cellulosic ethanol and stated that, statistically, the minimum fuel ethanol selling price was minimally affected by the feedstock and process pathway (conclusion attributed by the authors partly to data limitation), while there are other factors that had a pronounced impact on the minimum fuel selling price, such as production capacity (negative) or the capital cost (positive). The authors also stated that the model they developed indicated that every USD 1 million increase in the capital cost is estimated to raise the minimum fuel selling price by approximately 0.30 cents per gallon for an ethanol plant to break even, holding other variables constant [117].

One strategy employed by numerous researchers to address these bottlenecks and improve the economic viability of second-generation ethanol (2G ethanol) is the integration of a 1G2G facility. In other words, this entails combining a conventional first-generation ethanol plant with an attached biomass processing facility. This integration approach reduces the risks associated with implementing new technologies [29,31,119–121]. By incorporating annexed biomass processing units, certain unit operations, such as sugar concentration through evaporation, fermentation, and ethanol purification (including distillation, rectification, and dehydration), can be shared, thus enhancing the economic sustainability of the overall unit [29,31,120]. While lots of researchers focus on integrated 1G2G biorefineries, there are also studies that explore standalone 2G ethanol biorefineries [30,118,122].

Pretreatment remains a significant bottleneck for the economic feasibility of cellulosic ethanol facilities, primarily due to its complexity, high capital requirements, and the potential for increased greenhouse gas emissions [117]. Table 2 provides an overview of various examples of pretreatment, along with their operational conditions and advantages and disadvantages.

Table 2. Examples of some biomass pretreatment methods currently available and studied, with their operation conditions (temperature and pressure) and the existing bottlenecks that need to be overcome [32,46,123–125].

Pretreatment Category	Pretreatment Technique	Operation Condition	Advantages	Disadvantages
Chemical	Dilute acid	T = 150–220 °C P = SVP [a]	Simple, low cost and high xylose yields	Detoxification required, acid is corrosive and hazardous
	Dilute alkali	T > 100 °C P = SVP [a]	Low sugar degradation, efficient removal of lignin	High cost of alkalis, long residence time
	Ionic liquid	T = 80–170 °C P= AP [c]	Mild conditions, efficient dissolution of cellulose	High cost of ionic liquids, difficult to handle viscous solutions
Physicochemical	Hot water	T = 170–230 °C P > 5 MPa	Recover pure cellulose, no need for chemicals	High pressure is required, energy intense
	Steam explosion	T = 160–260 °C P = 0.69–4.89 MPa	High sugar yields, no need for chemicals	Formation of inhibitory compounds, harsh conditions
	AFEX [b]	T = 60–180 °C P = 2 MPa	Efficient lignin removal, low inhibitor formation	High pressure and temperature are required, high cost of ammonium recycling
	HC-assisted	T = 60 °C P = AP [c]	No inhibitor formation, mild conditions, simple system	Low solid content in the pretreatment reactor
Biological	Fungal/ bacterial	Specific to each microorganism	Low energy consumption, mild conditions, no inhibitor formation	Time consuming, part of fermentable sugar consumed, strict culture conditions required

SVP [a] = Saturated vapor pressure, AFEX [b] = Ammonium fiber explosion, AP [c] = atmospheric pressure.

Mechanical pretreatments, commonly employed as a preliminary step, utilize mechanical force to disrupt the primary cell wall, thereby increasing the surface area and enhancing cellulose accessibility [126]. Chemical pretreatments involve complete or partial removal of compounds from the lignocellulosic biomass. Examples include acid and alkaline treatment, steam explosion, sulfur dioxide explosion, ammonium fiber explosion, ionic liquid treatment, and others. These pretreatments exert diverse effects on the biomass, such as cellulose dissolution or crystallinity reduction, separation of lignin from cellulose and hemicellulose, lignin redistribution, hemicellulose removal, increased surface area and porosity, as well as reduction in thickness, volume, and particle size to break various chemical linkages [127]. Physicochemical pretreatments involve the modification of lignocellulosic components based on factors such as temperature and moisture content, leading, for example, to the removal of hemicellulose and lignin [128]. On the other hand, biological processes offer an alternative to physicochemical pretreatments by employing enzymes and microorganisms. However, these processes have certain drawbacks, such as longer reaction times and inhibitions caused by the formation of toxic compounds [47].

Alkali pretreatment, for example, is employed to remove lignin, acetyl groups, and uronic acids from biomass, thereby enhancing the accessibility of enzymes to the carbohydrate fraction of the biomass during the saccharification step. One of the key advantages of alkaline pretreatment is its ability to operate at lower temperatures, eliminating the need for reactors designed for harsh conditions as typically required in acid pretreatments [31,46]. Acid pretreatment, on the other hand, can be carried out using either low concentrations of acid at high temperatures or high concentrations of acid at low temperatures. Naturally, different effects on the biomass structure are achieved depending on whether dilute or concentrated acid solutions are used [29,46].

Regarding the physicochemical alternatives, steam explosion can be highlighted as one of the most studied alternatives [46,103]. Nevertheless, other new possibilities have been considered, such as ionic liquids [129], deep eutectic solvents [10], and hydrodynamic cavitation [32]. The hydrodynamic cavitation assisted process is an emerging pretreatment technology that offers high process yield in biomass pretreatment. This process is achieved through a sudden drop in pressure, which results in microbubble formation. The implosion of microbubbles generated during hydrodynamic cavitation creates 'hotspots' with localized high pressure and temperature, generating microjets and highly oxidant species which facilitate the fragmentation of biomass. The effect of cavitation is even more effective when combined with chemical reagents, such as peroxides, alkalis, and other additives [39]. This combination of physical and chemical effects makes hydrodynamic cavitation a promising approach for biomass pretreatment in the production of biofuels and other bioproducts [130].

In the context of biomass pretreatment, Mendes et al. [31] conducted a study on the utilization of alkaline sulfite pretreatment under mild and severe conditions for different sugarcane hybrids, considering a 1G2G biorefinery scenario. The study also investigated the effects of hydrolysis time (24 and 72 h) and pentose destination (treatment or co-fermentation). The results indicated that the less recalcitrant biomass, severe pretreatment conditions, longer hydrolysis time, and co-fermentation of pentoses led to higher ethanol yields. However, for electricity production, the opposite trend was observed. This outcome was expected since the increased availability of fermentable sugars favored ethanol production, while the reduced recalcitrant biomass was directed towards the cogeneration system [31]. Through the TEA, the authors discovered that the most favorable outcomes were achieved with mild condition pretreatment. However, even these optimal results did not prove to be economically attractive as the internal rate of return (IRR) fell below the minimum acceptable rate of return (MARR), suggesting that pretreatment remains a bottleneck in the process. Mendes et al. [31] further compared the final ethanol production costs (EPC) between 1G and 2G installations, considering the studied hybrids. The 1G EPC ranged from USD 0.337 to USD 0.477, while the 2G EPC ranged from USD 0.889 to USD 3.461. This comparison demonstrated that the EPC for 2G installations is significantly higher than that for 1G installations.

Vasconcelos et al. [29] investigated a pretreatment method using diluted acid while varying the solid content in the pretreatment reactor between 5% and 10%. The study revealed that the highest ethanol yield was achieved when the pretreatment involved a higher solid content and when the pentose fraction was co-fermented for ethanol production. On the other hand, for electricity generation, the scenario with 5% solids in the pretreatment reactor proved to be more favorable due to the lower amount of biomass processed for 2G ethanol production. This conclusion aligns with the findings of Mendes et al. [31]. Also, in the work of Vasconcelos et al. [29], the TEA revealed that the CAPEX and the chemical input prices for pretreatment had the most significant impact on the EPC of 2G ethanol. Sensitivity analysis indicated that a 20% reduction in the CAPEX and the chemical input costs could result in an IRR exceeding the MARR. Moreover, a 20% reduction in the CAPEX alone already improved the economic feasibility of 2G ethanol. The authors also observed that a higher solid content in the pretreatment reactor led to a reduced thermal demand but increased the operational expenditure (OPEX) more than the revenue generated from surplus ethanol production. Consequently, from an economic perspective, in that study, surprisingly, a higher solid content in pretreatment was unfavorable [29].

It is important to note that the scenario resulting in the maximum ethanol yield does not necessarily correspond to the scenario with the best internal rate of return (IRR). This discrepancy arises from the fact that less biomass is directed towards the cogeneration system, resulting in a reduced surplus of electricity sold to the grid. This finding aligns with the conclusions of Mendes et al. [31] and Dias et al. [131], underscoring that electricity production remains a significant revenue contributor for the facility.

In addition to the pretreatment step, another factor that significantly impacts the economic feasibility of 2G ethanol units is the cost of enzymes required for the enzymatic hydrolysis process [30]. Furthermore, enzymes can also have an adverse effect on the environmental sustainability of these facilities, as their production may involve fossil-reliant purification procedures or high energy consumption [132].

Carpio et al. [30] conducted an evaluation of on-site production of cellulolytic enzyme blends utilizing the microorganisms (MO) *Trichoderma reesei* and *Aspergillus awamori*, instead of purchasing them from retailers. The cost of enzymes can contribute around USD 0.40 per gallon of ethanol to the EPC. This cost is attributed to the purification steps required when purchasing from retailers, which can be avoided in on-site production. Additionally, transportation and refrigeration costs can also be eliminated [30]. However, the TEA demonstrated that on-site enzyme production would increase the EPC, primarily due to the higher CAPEX associated with the larger size of tanks required and the acquisition of raw materials. This finding indicated the non-viability of the on-site enzyme production process in the conditions simulated by those authors. Nevertheless, the authors considered a scenario where enzyme production was limited to a single engineered fungus strain, which reduced the on-site enzyme production cost by a factor of 20 times. This indicates that enzyme production remains a significant economic bottleneck for cellulosic ethanol process.

An alternative approach to address the restrictions imposed by enzyme costs is a CBP, which involves integrating enzyme production, enzymatic hydrolysis, and fermentation into a single bioreactor [118]. Dempfle et al. [118] evaluated a CBP for ethanol production and compared it with conventional processes, considering different pretreatment methods for a CBP (pure steam) and the base case (diluted acid). The CBP has the potential to reduce the CAPEX by requiring less equipment; however, during the TEA, a different behavior was observed. There was a 4.77% increase in the CAPEX due to the requirement for more robust equipment when using a different pretreatment method. On the other hand, a 51.4% reduction in the OPEX was observed due to reduced chemical reagent demand. The authors concluded that 57% of the OPEX is directly associated with the change in pretreatment, while 47% is directly associated with the CBP.

In relation to process operation, Ranganathan [133] examined various scenarios for 2G ethanol production, including separate fermentation of pentoses and hexoses as well as co-fermentation of pentoses and hexoses. The author concluded that co-fermentation yielded superior economic results, as it resulted in a lower operational expenditure (OPEX), capital expenditure (CAPEX), and minimum selling price (MSP) as compared to separate fermentation. Specifically, for co-fermentation, the OPEX was USD 4.3 million per year, the CAPEX was USD 89.6 million, and the MSP was USD 0.563/L. In contrast, for separate fermentation, the corresponding figures were USD 55.5 million, USD 91 million, and USD 0.627/L, respectively. These findings demonstrate that a higher level of integration leads to improved economic outcomes for the biorefinery.

Another primary bottleneck for cellulosic ethanol production is the utilization of different fractions of biomass. Mendes et al. [31], Vasconcelos et al. [29], and Carpio et al. [30] considered various scenarios for the pentose fraction, although there were differences in the scenarios evaluated by each author. Figure 1 illustrates a schematic representation of the pentose fraction's destiny as considered in these three studies. It is worth noting that the authors employed different pretreatment techniques. Vasconcelos et al. [29] and Carpio et al. [30] used pretreatments that resulted in a liquid fraction rich in pentoses. However, Mendes et al. [31] employed a pretreatment technique that did not solubilize hemicellulose, thereby yielding a solid fraction that still contained significant amounts of hemicellulose, which would be hydrolyzed in subsequent steps.

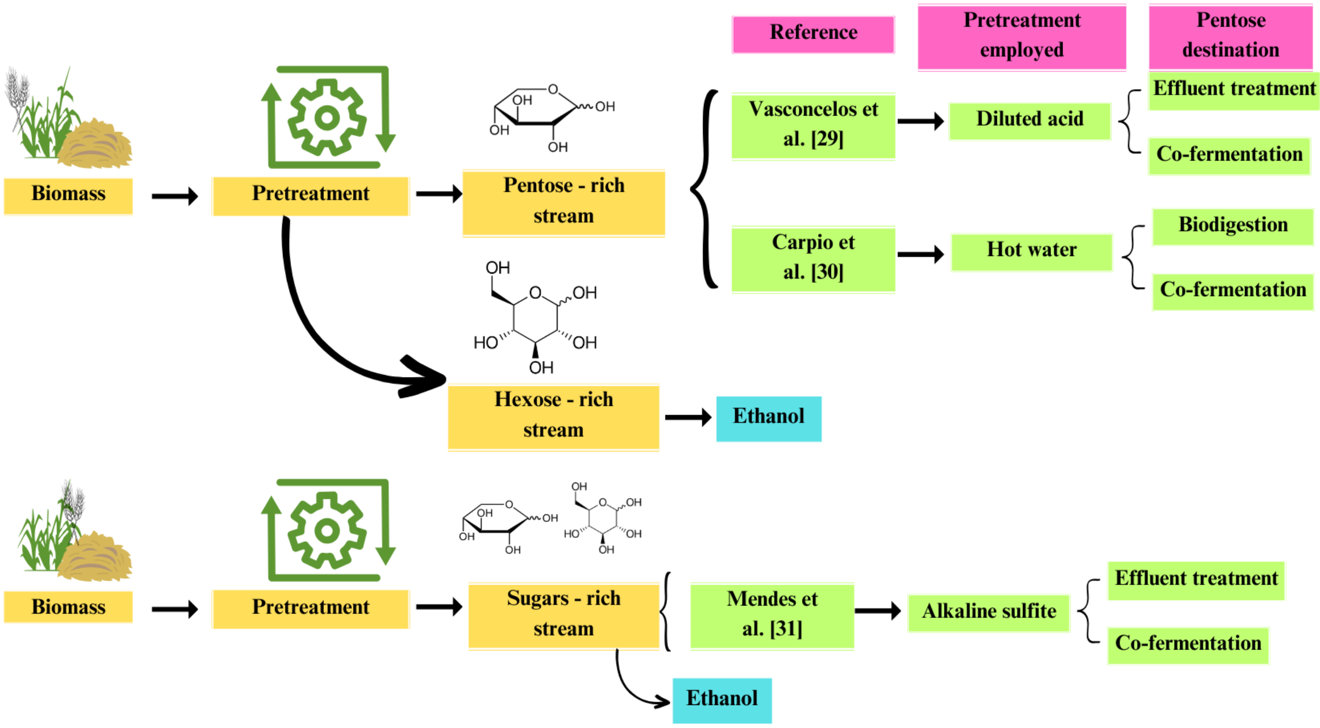

Figure 1. Illustrative scheme of some possible destinies of the pentose fraction of the biomass. Every author considered two different pentose destinies, but all authors considered, in at least one scenario, that pentose is co-fermented to ethanol. References: Vasconcelos et al. [29], Carpio et al. [30], Mendes et al. [31].

Mendes et al. [31] and Vasconcelos et al. [29] explored two different scenarios for the pentose biomass fraction: sending it directly to effluent treatment or co-fermenting it together with the hexoses. Both studies concluded that co-fermentation yielded better economic results due to higher ethanol yields and an increased surplus of electricity available for sale to the grid. This increase in electricity generation can be attributed to the higher steam consumption required for pentose concentration and the larger quantity of wine to be distilled when considering pentose co-fermentation [29–31].

In similar way, Carpio et al. [30] examined a comparable scenario, but instead of sending the pentose fraction to effluent treatment, they considered biodigestion for biogas production, alongside enzyme residues in one scenario. Biodigestion of pentoses led to a lower OPEX, but also lower income. However, the operational cash flow for pentose fermentation was slightly better, demonstrating that the co-fermentation of pentose remains the superior option from an economic standpoint [30]. Furthermore, the concentration of the pentose stream can positively impact the process, as it reduces water demand, and the water recovered during C5 evaporation can be recycled back into the process [30].

As demonstrated in this section, cellulosic ethanol continues to confront significant bottlenecks on its path to achieving economic sustainability. Despite numerous studies conducted on the subject, there is no singular solution that can independently enhance the economic viability of 2G ethanol facilities. However, an additional strategy which was not discussed in this section but will be explored in the next section is product diversification within the facility. This strategy aims to improve the economic sustainability of the facility by expanding its range of products.

4. Product Diversification on 2G Ethanol Biorefineries

Product diversification in 2G ethanol biorefineries can offer a viable solution to address the economic sustainability challenges faced by the facilities. This strategy has already been implemented in Brazilian 1G ethanol biorefineries, where the production of sugar, ethanol, and electricity from sugarcane is directed towards obtaining the most valuable product at any given time, thereby increasing revenues [134,135].

In 2G ethanol biorefineries, one of the primary approaches to promote product diversification is by valorizing a side-stream of the process. Considering only strategies with published articles dealing with TEA, the main strategies to valorize side-streams include its use as a substrate for MO growth [135], either subjected to biodigestion for biogas production [136] or processed to obtain different products [33,34,36–38,129,133]. Figure 2 provides an overview of the strategies employed to enhance the economic viability of 2G ethanol biorefineries and highlights some of the potential products that can be obtained. Additionally, Table 3 summarizes the articles that are discussed in this section.

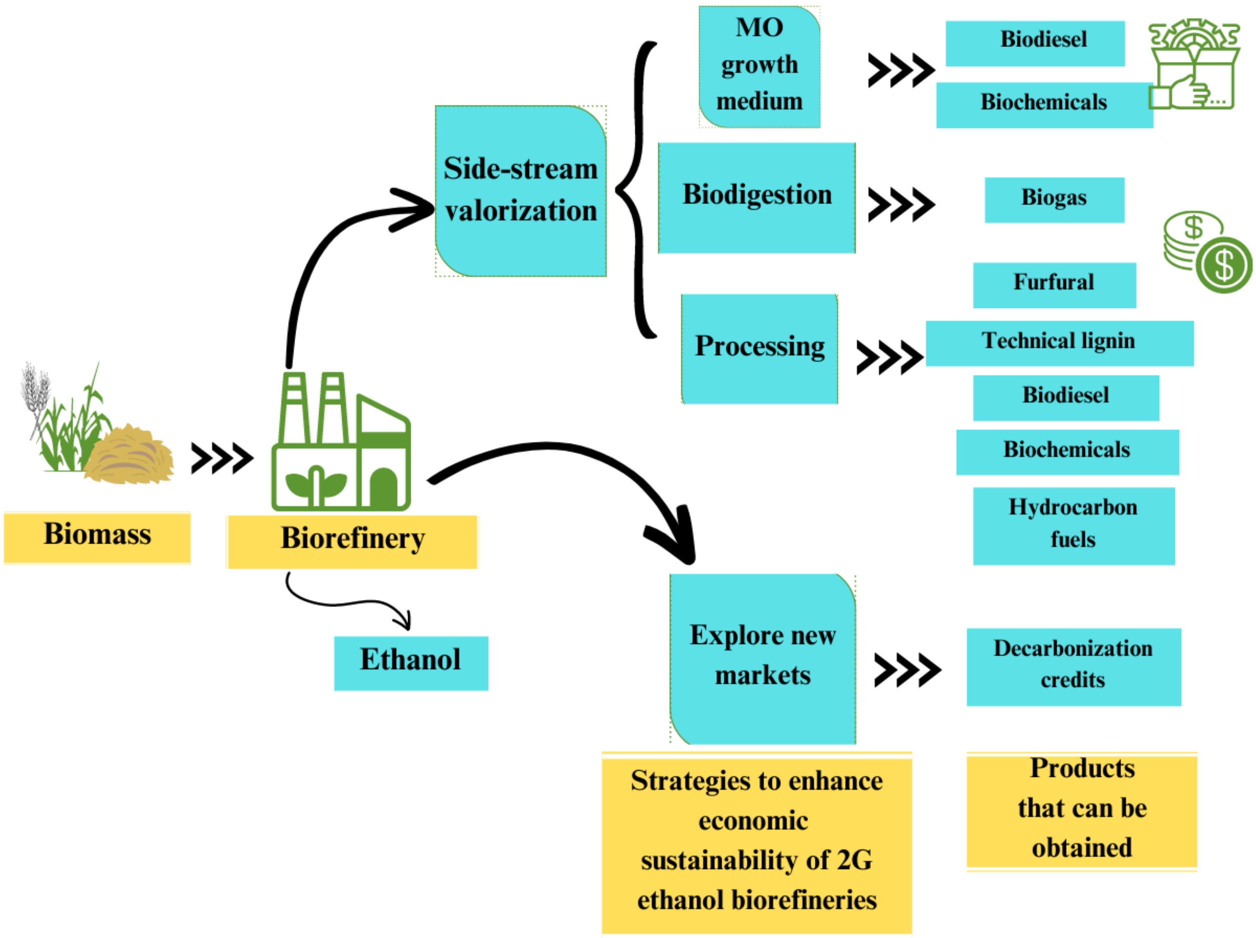

Figure 2. Some of the main strategies evaluated to the enhance economic sustainability of 2G ethanol biorefineries, considering by-product processing and maximum sugar assimilation for production of diverse bioproducts.

Hossain et al. [33] and Ntimbani et al. [34] conducted studies on the co-production of furfural alongside ethanol, which is an interesting approach considering that furfural is typically considered a biological inhibitor [33]. In their study, Hossain et al. [33] investigated furfural production from diluted acid pretreatment, where a portion of hemicellulose is degraded into furfural. On the other hand, Ntimbani et al. [34] employed a specific step for furfural production, with the remaining solid residue is used for ethanol production through a simultaneous saccharification and fermentation (SSF) process.

Table 3. Studies about product diversification on 2G ethanol biorefineries that completed a techno-economic assessment (TEA).

Strategy	Product Obtained	Biomass	Reference
Processing	Furfural	Corn stover	Hossain et al. [33]
	Technical lignin	SCB [a]	Silva et al. [129]
	Furfural	SCB [a] and harvest residues	Ntimbani et al. [34]
	Biodiesel	Industrial hemp	Viswanathan et al. [36]
	Furfural and biochemicals	Rice straw	Ranganathan et al. [133]
	Biochar and hydrocarbon fuels	SCB [a]	Wang et al. [38]
	Biodiesel	Energy cane	Kumar et al. [37]
Biodigestion	Biogas	Vinasses from a 1G2G integrated sugarcane biorefinery	Longati et al. [136]
Microorganism growth medium	Carotenoids	CO_2 from fermentation step in a 1G2G integrated sugarcane biorefinery	Albarelli et al. [39]
Explore new markets	Decarbonization credits	SCB [a]	Carpio et al. [30]
		SCB [a] and trash	Pinto et al. [119]

[a] Sugarcane Bagasse.

Through a TEA, Hossain et al. [33] concluded that the co-production of 2G ethanol and furfural resulted in a profitability of USD 3.28 million, which increased significantly to USD 49.95 million when heat integration was implemented. Similarly, Ntimbani et al. [34] compared the co-production of furfural and 2G ethanol with the sole production of 2G ethanol. The results showed that furfural co-production improved the economic viability of the installation, with a higher internal rate of return (IRR) and a lower minimum selling price (MSP): 12.78% and USD 0.42/L, respectively, as compared to 10.18% and USD 0.595/L when only ethanol was produced. Additionally, Ntimbani et al. [34] concluded that due to the high yields achieved for furfural and ethanol, the biorefinery became less dependent on electricity sales.

Another side-stream derived from the processing of lignocellulosic biomass is the lignin-rich stream, which is typically directed towards cogeneration systems for steam and electricity production. However, lignin can be utilized as a platform for chemical building blocks, adding value to the overall process [129]. In a study conducted by Silva et al. [129], the co-production of technical lignin and 2G ethanol was examined using a protic ionic liquid pretreatment. The authors identified some potential bottlenecks in the process, such as the need for efficient washing before enzymatic hydrolysis to remove any biological inhibitors and the high steam consumption required for technical lignin evaporation. Despite these challenges, the process proved to be economically viable and demonstrated improvements in economic parameters when compared to a 1G2G facility. As can be seem in Table 4, there was a positive impact from product diversification on the installation reported by Silva et al. [129]. The decrease in the capital cost can be attributed to a reduction in overall infrastructure, particularly in the hydrolysis and fermentation sections of the biorefinery. The enhanced economic feasibility of the biorefinery can be directly attributed to the co-production of technical lignin, which significantly improved the overall economic parameters.

Table 4. Summary of economic parameters obtained from reports about product diversification in 2G ethanol biorefineries.

	Operation	Ethanol Production	Bioproduct Obtained	CAPEX [c] (million)	OPEX [d] (million)	IRR [e] (%)	NPV [f] (million)	MSP [g]	Reference
NPD [a] IPD [b]	Only 2G biorefinery	11,184 kg/h 2452 kg/h	Furfural	- -	- -	10.18 12.78	- -	USD 0.595/L USD 0.42/L	Ntimbani et al. [34]
NPD [a] IPD [b]	Integrated 1G2G biorefinery	393.8 kt/year 359.1 kt/year	Technical lignin	USD 550.9 USD 512.7	- -	17.06 19.09	USD 389.4 USD 480.2		Silva et al. [129]
NPD [a] IPD [b]	Only 2G biorefinery	83.45 ton/day 83.45 ton/day	Furfural, furfural and biochemicals	USD 91 USD 195	USD 55.5 USD 55.5	- -	- -	USD 0.627/L USD 0.25/L	Ranganathan [133]
NPD [a] IPD [b]	Only 2G biorefinery	256,000 m^3/year 256,000 m^3/year	Biochar and hydrocarbon fuels	USD 436 USD 427–460				USD 1.623/gal USD 1.494–1.673/gal	Wang et al. [38]
NPD [a] IPD [b]	Integrated 1G2G biorefinery	94.7 m^3/h 91.7 m^3/h	Biogas	- -	- -	13.6 6.1	USD 4.63 USD −7.13	- -	Longati et al. [136]

[a] Not including product diversification, [b] Including product diversification, [c] Capital expenditure, [d] Operational expenditure, [e] Internal rate of return, [f] Net present value, [g] Minimum ethanol selling price.

Table 4 provides a summary of the selected results obtained from other studies discussed in this section from the economic viewpoint.

In the study conducted by Ranganathan [133] various scenarios of product diversification were evaluated, specifically considering the co-production of furfural and/or biochemicals from lignin. The author concluded that the application of product diversification resulted in improved economic outcomes in all scenarios, particularly in terms of the minimum selling price (MSP) of ethanol. The scenario with the most extensive product diversification, involving the co-production of furfural, biochemicals, and 2G ethanol, yielded the best MSP for ethanol at USD 0.25/L, despite having a higher capital expenditure (CAPEX) of USD 195 million and an operational expenditure (OPEX) of USD 55.5 million. This can be attributed to the higher selling price of biochemicals and furfural as compared to ethanol, demonstrating that product diversification is an effective strategy for enhancing the economic feasibility of 2G ethanol production.

Wang et al. [38] conducted a study on the production of biochar and hydrocarbon fuels through the pyrolysis of lignin-rich residues from cellulosic ethanol. The authors evaluated two scenarios: one focused on biochar production alone, and the other involved the production of both biochar and hydrocarbon fuels. These scenarios were compared to a base scenario where lignin-rich residues were directed to a cogeneration system for burning. Through a TEA, as shown in Table 4, the authors found that biochar production alone resulted in a lower CAPEX (USD 427 million) but led to a higher ethanol MSP of USD 1.673/gal compared to the base scenario (a CAPEX of USD 436 million and an MSP of USD 1.623/gal). On the other hand, the biochar + hydrocarbon fuels scenario exhibited a different pattern: a higher CAPEX (USD 460 million) but a lower MSP of USD 1.494/gal [38]. This trend of an increasing CAPEX with a decreasing MSP was observed in several other studies already presented in this review [39,118,133]. In the work of Wang et al. [38], the authors also conducted sensitivity analysis and found that the large-scale production of biochar + hydrocarbon fuels resulted in a higher ethanol MSP instead of a decrease, indicating that this operation should be carried out on a larger scale [38].

Another approach to diversifying products in a cellulosic ethanol biorefinery is by utilizing side-streams as substrates for obtaining bioproducts in a microbiological way. Longati et al. [136] conducted a comparison of three different scenarios: 1G, 1G2G with pentose fermentation, and 1G2G with pentose biodigestion. They also examined similar scenarios but with the addition of biogas production from vinasse. The biogas generated was directed to the cogeneration system for steam and electricity production. The authors concluded that biogas production had a positive impact on the economic parameters of the biorefinery. However, in the case of 1G2G + C5 biodigestion, economic feasibility was not achieved, which aligns with the findings of Carpio et al. [30]. In the work of Longati et al. [136], a 1G2G + C5 biodigestion scenario resulted in a negative net present value (NPV) of USD −7.13 million and an IRR of 6.1%, which is lower than the MARR of 11%, as shown in Table 4. On the other hand, better results were achieved with 1G and 1G2G + C5 fermentation, with an IRR of 19.7% and 13.6% and an NPV of USD 11.5 million and USD 4.63 million, respectively [136]. From an LCA, authors could establish that scenarios involving 1G2G biorefineries and C5 fermentation exhibited the best values for impact categories, such as fresh water aquatic ecotoxicity (FWAET) and marine aquatic ecotoxicity (MAET). Following 1G2G plus C5 fermentation, the 1G2G scenario with C5 biodigestion displayed improved environmental impact, with 1G facilities being regarded as the worst-case scenario.

Albarelli et al. [39] conducted a study on microalgae growth utilizing the CO_2 released during alcoholic fermentation. The microalgae biomass obtained from this process has the potential to yield high-value products, such as carotenoids [39]. The results from the simulated scenario were compared to a similar 1G2G biorefinery that did not include the microalgae growth and harvest section. The microalgae growth process allowed for the capture of 64.2 kg of CO_2 per ton of sugarcane processed, which demonstrated a positive environmental impact on ethanol production. In addition to the environmental aspect, microalgae growth could also enhance the economic sustainability of the biorefinery. The CAPEX for the microalgae scenarios was higher (ranging from USD 400 million to USD 500 million in most scenarios) compared to the 1G2G only scenario (ranging from USD 300 million to USD 400 million). However, the revenue was also higher due to the production of high-value products like carotenoids [39]. The authors identified microalgae harvest as a bottleneck since the microalgae biomass needs to be dried before extracting the compounds. They also proposed a new potential product diversification by utilizing the side-stream obtained after carotenoid extraction, which is still rich in carbohydrates and proteins [39].

The articles discussed thus far have focused on cellulosic ethanol production from biomass sources with a low lipid content, such as corn stover or SCB. However, there are lignocellulosic biomass examples that have a higher lipid content, such as industrial hemp. From these lipids, it is possible to produce biodiesel, which is one of the primary biofuels used for transportation [36].

Viswanathan et al. [36] conducted a study on the utilization of industrial hemp to produce 2G ethanol and biodiesel. What sets this study apart is that biodiesel is considered the main product, whereas other studies prioritize ethanol production. The authors examined three scenarios with varying oil content in the biomass: 2%, 5%, and 10%. The findings revealed that a higher oil content led to better results in terms of the TEA, primarily due to increased biodiesel production, which carries a higher value compared to ethanol. Furthermore, the study demonstrated that the scenario with 10% oil content resulted in improved CAPEX (USD 499.70 million) and OPEX (USD 143.89 million) as compared to the 2% (a CAPEX of USD 464.41 million and an OPEX of USD 149.86 million) and 5% (a CAPEX of USD 512.09 million and an OPEX of USD 146.32 million) scenarios. In terms of the EPC, the authors found a value that was USD 1.22/L lower than that reported by Mendes et al. [31], highlighting the economic viability of biodiesel as a valuable product for diversifying bioproducts in 2G ethanol biorefineries. Additionally, the production of biodiesel generates glycerol as a by-product, which can also be sold [36].

Kumar et al. [37] conducted a study on the co-production of biodiesel and ethanol using engineered energy cane within a 1G2G ethanol facility. Like Viswanathan et al. [36], three different oil content levels in the biomass (0%, 5%, and 7.7%) were proposed. However, Kumar et al. [37] also examined two different scenarios: sending the biomass directly to the cogeneration system (scenario 1) or producing 2G ethanol (scenario 2). The findings showed that co-producing 2G ethanol, rather than sending the biomass directly to the cogeneration system, resulted in a significant increase in ethanol production by a factor of 5.5 (from 10.4 million gallons to 57 million gallons). Additionally, the authors found that a higher oil content in the biomass led to a decrease in 2G ethanol production; this is similar to the findings of Viswanathan et al. [36], which can be attributed to the lower cellulose content in the biomass. Through a TEA, the authors observed that scenarios involving 2G ethanol production had CAPEX values that were over 60% higher, ranging from USD 220.5 million to USD 244 million, as compared to scenarios without 2G ethanol production, where the CAPEX ranged from USD 364.4 million to USD 406.6 million. This increase in the CAPEX was primarily due to the requirements of the pretreatment reactor and cogeneration equipment [37]. The authors concluded that the production of 2G ethanol had a negative impact on a biodiesel biorefinery. However, it is important to note that in both Kumar et al. [37] and Viswanathan et al. [36], biodiesel was considered the main product to be obtained. Taking a different perspective, if ethanol is considered the main product, product diversification by including biodiesel as a secondary product could potentially enhance the economic sustainability of the biorefinery.

One interesting strategy, although not fully consolidated in the market, is the sale of decarbonization credits on the stock market. This is possible because 2G ethanol production enhances biofuel generation without increasing the planted area, thus avoiding deforestation and reducing greenhouse gas emissions [137]. Pinto et al. [119] conducted a TEA and an LCA for 1G2G biorefineries that utilized soybean protein to mitigate the action of biological inhibitors. In their TEA, the authors considered the commercialization of decarbonization credits as one of the revenue streams and found that this could significantly benefit the economic viability of cellulosic ethanol production. Similarly, Carpio et al. [30] also evaluated the sale of decarbonization credits in their study and came to the same conclusion as Pinto et al. [119] regarding the positive impact of this practice on the economic feasibility of the biorefinery. Using an LCA, Pinto et al. [119] also found that the biodigestion of vinasse yielded positive effects on the values of impact categories, including the FWAET and the MAET. The scenario incorporating 1G2G along with vinasse biodigestion demonstrated a reduced environmental impact as compared to scenarios involving 1G without vinasse biodigestion and 1G2G without vinasse biodigestion.

Water usage affects not only the LCA but also the TEA, as it can significantly impact steam consumption in the concentration and distillation/dehydration processes. Additionally, water can also be utilized in the washing section, introducing the potential for the negative effects on the TEA due to the associated costs of water usage [119].

This is a very attractive approach since it does not require additional investment for the commercialization of decarbonization credits, and 2G ethanol has great potential in this regard. It should be noted that decarbonization credits are not yet fully consolidated and their prices can fluctuate [30,119].

As depicted in Table 4, the product diversification approach within a 2G ethanol biorefinery demonstrates the potential to enhance the economic sustainability of these facilities. Besides its potential to, in some cases, decrease expenditures, including CAPEX and OPEX, product diversification can also boost revenues by introducing new products typically derived from side-streams or by-products. Upon closer examination, product diversification emerges as a strategic avenue for valorizing side-streams and by-products within the context of a biorefinery.

5. Future Perspectives on Product Diversification for 2G Ethanol Biorefineries

As shown in the previous sections, 2G or 1G2G ethanol biorefineries still face major difficulties in terms of economic sustainability. However, the strategy of diversifying the products obtained from biomass appears to be an effective approach to overcome these challenges. It has been demonstrated that it is possible to obtain multiple products from biomass, and various strategies can be employed, ranging from directing a portion of the sugar for the obtainment of different products to valorizing side-streams of the process. Furthermore, there is an opportunity to leverage new marketplaces and explore the potential of promoting decarbonization credits as a potential new revenue stream for lignocellulosic refineries.

There are still other high-value products that could enhance the economic feasibility of 2G ethanol, such as biopigments [57], biopolymers [79], biosurfactants [138], or xylitol [139]. In addition to product diversification, it is important to explore new technologies that can improve economic parameters. One example is the study of new pretreatment technologies, including hydrodynamic cavitation-assisted pretreatments [32]. By exploring these avenues, further advancements can be made in the economic viability of 2G ethanol production. There are some published articles which evaluated the production of these and other bioproducts from lignocellulosics, as the following examples describe.

Table 5 shows a compilation of articles discussed in Section 5, focusing on emerging bioproducts that can be derived from lignocellulosic biomass and have the potential for production within a biorefinery framework alongside 2G ethanol. Details about the specific bioproduct obtained, the substrate used, and the strategy for incorporating these products into a 2G ethanol biorefinery are presented.

Table 5. Studies about possible product diversification of 2G ethanol biorefineries: articles highlight potential products that can be produced alongside 2G ethanol in a biorefinery context but without considering a techno-economic assessment.

Strategy	Biomass/Side-Stream	Product Obtained	Reference
Use part of the carbohydrate fraction	SCB [a]	Biopigments	Terán-Hilares et al. [57]
	SCB [a]	Pullulan	Terán-Hilares et al. [79]
	Oat and soy hulls	Xylitol	Cortivo et al. [140]
	SCB [a]	Green-hydrogen	Ongis et al. [141]
Side-stream/by-product valorization	Pentose fraction	Succinic acid	Xu et al. [142]
	Pentose fraction	Biosurfactant	Marcelino et al. [138]
	Vinasse	Xylitol	Prado et al. [139]
	Black liquor	Biogas	Gomes et al. [143]
	Black liquor + SFEH [b]	Lignosulfonate	Heinz et al. [144]

[a] Sugarcane bagasse, [b] Solid fraction from enzymatic hydrolysis.

Biopigments from *Monascus* are high-quality and edible natural pigments that are produced by MOs. These pigments have a wide range of applications in various industries, including food, cosmetics, and pharmaceuticals. In addition to their coloration properties, biopigments also possess biological functions, such as antibacterial, antioxidant, and anti-cancer activities [145]. These biopigments offer a sustainable alternative to the synthetic colorants commonly used in various industries.

In the study conducted by Terán-Hilares et al. [57], the production of red pigments from *Monascus ruber* was investigated using SCB hydrolysate under different light conditions. The authors discovered that the utilization of SCB hydrolysate in the production of red pigments resulted in a significant improvement as compared to a synthetic glucose-based medium. Specifically, the red pigment production increased from 7.45 AU_{490nm} in the glucose-based medium to 18.71 AU_{490nm} when the SCB hydrolysate was employed. Based on these findings, the authors concluded that the incorporation of red pigments from *M. ruber* could be a valuable addition to biorefineries.

Pullulan is a biopolymer produced by *Aureobasidium pullulans*, and it finds applications in various industries, such as cosmetics, food, packaging, and pharmaceuticals. Similarly, pullulan, like biopigments, also possesses several interesting biological properties, including non-toxicity, biodegradability, biocompatibility, adhesive properties, and non-mutagenicity, among others [146]. By using biomass, Terán-Hilares et al. [79] reported the production of pullulan from SCB hydrolysate, with the assistance of blue LED lights. Using a bubble column reactor, the authors were able to achieve a pullulan concentration of 18.64 g/L, corresponding to a yield of 0.48 g/g. These results show promising potential for the industrial-scale application of pullulan production. Therefore, the study demonstrated that pullulan production from SCB hydrolysate could serve as a valuable product obtained within the context of biorefineries [79].

Considering the studies conducted by Terán-Hilares et al. [57] and Terán-Hilares et al. [79], a portion of the enzymatic hydrolysate that is typically directed towards ethanol production would be allocated to produce other bioproducts. This diversion would result in a reduction in ethanol production. However, it has the potential to enhance the economic viability of these biorefineries due to the significantly higher added value of biopigments and pullulan as compared to ethanol. Additionally, while ethanol is generally treated as a commodity traded in large quantities, pullulan and biopigments are specialty products, which means that their production would be on a smaller scale.

Compounds such as organic acids could also emerge as potential candidates for diversification in 2G ethanol biorefineries. Xu et al. [142] conducted a study on succinic acid production from SCB by co-fermenting hexoses and pentoses to produce both succinic acid and ethanol. The study successfully achieved desirable concentrations of ethanol (22 g/L) and succinic acid (22.1 g/L), along with promising yields: ethanol (0.086 g/g_{SCB})

and succinic acid (0.087 g/g_{SCB}). This demonstrates the feasibility of the simultaneous production of two different bioproducts utilizing distinct MOs: *Saccharomyces cerevisiae* for ethanol and *Actinobacillus succinogenes* for succinic acid. The authors further noted that the CO_2 released during alcoholic fermentation was effectively utilized for succinic acid production, like the strategy employed by Albarelli et al. [39]. Overall, the process studied exhibits great potential within the context of biorefinery integration.

Considering the approach taken in previous studies, such as Mendes et al. [31], Vasconcelos et al. [29], Carpio et al. [30], and Longati et al. [136], the valorization of pentose fractions proves to be crucial for ensuring the economic sustainability of biorefineries. In line with this, Marcelino et al. [138] conducted a study on the production of biosurfactants from hemicellulosic hydrolysate derived from SCB. Additionally, Prado et al. [139] explored the utilization of pentose-rich vinasse for xylitol production. These investigations highlight the potential of pentose valorization as an important aspect for enhancing the economic viability of biorefineries.

Biosurfactants are amphipathic molecules that possess emulsifying and/or surfactant properties. Like biopigments and pullulan, biosurfactants also exhibit interesting biological properties, such as high biodegradability, low toxicity, antimicrobial effects, and potential antitumor activity [147].

Marcelino et al. [138] conducted a screening of various yeasts to produce biosurfactants from hemicellulosic hydrolysate, both detoxified and non-detoxified. Through the screening process, the authors identified a yeast strain capable of volumetric biosurfactant production at a rate of 0.167 g/(L·h), demonstrating promising emulsifying properties. The authors emphasized the significance of detoxification as a critical step for utilizing the hydrolysate, which may pose a potential bottleneck for biorefineries. Nonetheless, Marcelino et al. [138] affirmed the viability of biosurfactant production within a biorefinery context.

Prado et al. [139] conducted a study on the fermentation of vinasse to fully utilize the sugars derived from SCB. The employed pretreatment technique, unlike alkaline sulfite [31] or diluted acid, does not solubilize hemicellulose, resulting in an enzymatic hydrolysate rich in glucose and xylose [32]. Initially, fermentation was carried out to produce 2G ethanol, which was then subjected to distillation. Subsequently, a second fermentation of the vinasse was conducted to obtain xylitol, a high-value sweetener widely used in the food and pharmaceutical industries [139,148]. The authors achieved ethanol and xylitol concentrations of 50 g/L and 32 g/L, respectively, corresponding to yields of 0.41 g/g for ethanol and 0.55 g/g for xylitol. Based on their findings, the authors concluded that the co-production of xylitol in high concentrations is suitable for product diversification within a biorefinery context.

Another study about xylitol production from lignocellulosic biomass was reported by Cortivo et al. [140], that utilized a genetically modified strain of the yeast *Saccharomyces cerevisiae* to produce both ethanol and xylitol. They used hydrolysates from oat and soy hulls for this purpose. When hydrolysates containing similar concentrations of glucose and xylose were used, the consumption of xylose was approximately 35% under anaerobic conditions. However, when hydrolysates primarily composed of xylose were used, approximately 73% of the xylose was consumed, and ethanol was produced with a yield of 0.33 g/g. In bioreactor cultures with limited oxygen supply, around 65% of the xylose was consumed, and the main product obtained was xylitol, reaching a final concentration of 8.17 g/L.

Lignin valorization is an essential aspect for the economic sustainability of biorefineries since it is typically either burned in the cogeneration system or directed to effluent treatment. However, lignin has the potential to yield various products that can enhance the economic feasibility of 2G ethanol biorefineries. These products include aerogels, resins, carbon fiber, activated carbon, fillers for materials, and thermosetting polymers [149,150].

Regarding the utilization of black liquor (lignin + hemicellulose) and the residual solid fraction from enzymatic hydrolysis, Gomes et al. [143] conducted a study on biogas production. From anaerobic digestion, they achieved biogas production of 563.59 NmL/g_{COD}

for black liquor and 57.78 NmL/g_{COD} for residual solids. The authors also conducted an economic analysis of potential revenues from electricity sales and determined that a profitability of USD 18.36/ton_{SCB} could be achieved. Gomes et al. [143] concluded that the process is suitable for integration into a biorefinery, although further energy integration is required.

Still on the valorization of black liquor and the residual solid fraction from enzymatic hydrolysis, Heinz et al. [144] conducted a study on utilizing these two streams for lignosulfonate production from SCB. The combined stream obtained from the union of these side-streams was re-sulfonated to enhance the concentration of lignosulfonate in the liquid stream. The authors were able to recover 57.3% of lignin from SCB, and, based on the characterization of the lignosulfonate, they suggested that the resulting stream could be suitable for various applications. This indicates that the process could be integrated into a 2G ethanol biorefinery.

Another product that can be obtained from lignocellulosic biomass is green hydrogen, which is a recent research trend in biofuel development. Ongis et al. [141] conducted a study on the use of biogas and biomethane for green hydrogen production using an autothermal process. This production process could be integrated with 2G ethanol biorefineries by using biogas produced from vinasse digestion, as demonstrated by Longati et al. [136] or by utilizing the pentose stream for biogas production [29,31]. Additionally, valorization of black liquor and of the residual solid fraction from enzymatic hydrolysis can also contribute to biogas production [143]. Digesting pentose to biogas may be more economically attractive since hydrogen prices are higher than ethanol prices in the market [117,151].

Still on energy production, although the production of high-value biochemicals holds great importance in a biorefinery context, several studies in the literature also consider the incorporation of bioelectricity generation from residues and/or agro-industrial by-products. For instance, apple pomace, a residue from apple processing, can be utilized in biorefineries for anaerobic digestion, leading to the production of biogas. This biogas can then be converted into electricity using a combined heat and power system [109]. In the case of an integrated biomass-to-energy biorefinery, the combination of straw and sawdust gasification and pyrolysis was proposed, resulting in high energy efficiency and benefits, ultimately maximizing the electricity generation of the system [152].

Animal feed biorefineries are also important alternatives for the recovery of residues and by-products from plant biomass. These biorefineries integrate biotechnological processes to convert biomass into high-quality ingredients for animal feed [153]. In a study conducted by Gómez et al. [154], the production of nutrient blocks and silage from agro-industrial banana residues was evaluated, and it was indicated that when mixed with corn forage, it increased the nutritional content for feeding dairy cattle [154]. Another category of important biorefineries for animal feed is green biorefineries, which utilize residues from legumes and grasses, serving as an important source of proteins, fibers, sugars, and minerals for feeding ruminants [155]. It was reported by Stødkilde et al. [156] that the inclusion of leaf protein extract biorefinery in pig feed increased the percentage of meat at slaughter linearly and the content of omega-3 fatty acids.

As presented in this section, there is a wide range of bioproducts that can be obtained from lignocellulosic biomass. These products can be derived from various components, including the assimilation of carbohydrates (hexoses and pentoses), utilization of macromolecules such as lignin, or even the utilization of side-streams such as CO_2 released during alcoholic fermentation. These products have the potential to be co-produced in a 2G ethanol biorefinery. However, there is a lack of simulation and TEA studies that consider the integration of these products. Therefore, there is significant potential for conducting such studies to evaluate the impact of this production on the economic sustainability of these biorefineries.

Furthermore, there is a significant opportunity to explore integration processes where one co-product obtained from the biorefinery is utilized for other applications within the same facility. For example, studies that focus on biogas production and its utilization for green hydrogen represent a promising avenue to enhance the economic sustainability of 2G ethanol biorefineries. However, there is a lack of such studies in the literature. Therefore, there is a tremendous opportunity to delve into these integration processes and uncover their potential benefits.

In addition to product diversification, improving technologies to produce 2G ethanol and other bioproducts is also a crucial approach that should be considered to enhance the economic feasibility of lignocellulosic biomass biorefineries. New pretreatment technologies, such as hydrodynamic cavitation-assisted processes, have not been extensively studied in TEAs. Therefore, there is a significant opportunity to conduct these studies and gain a better understanding of the potential benefits and technological advancements associated with each bioproduct.

6. Conclusions

Second-generation ethanol is a great alternative to increase global biofuel production without deforestation in new areas or creating competition with food supply chains. Indeed, 2G ethanol represents an excellent alternative to avoid dependence on fossil fuels. However, 2G ethanol facilities still face challenges in achieving economic sustainability due to well-known bottlenecks, such as the biomass pretreatment step, for example. One strategy with promising results is product diversification in the biorefinery portfolio.

As demonstrated in this review, diversifying the bioproducts obtained in a biorefinery can improve economic feasibility, and various strategies can be applied. Indeed, there is a wide range of possibilities to implement product diversification within 2G ethanol biorefineries. This study highlighted the potential of valorizing side-streams to produce different valuable products, such as bio-based chemicals, furfural, lignin derivatives, and additional biofuels, like biodiesel and hydrocarbon fuels. Additionally, it showcased the opportunity to explore new markets for the commercialization of decarbonization credits.

Furthermore, different authors have outlined prospective novel products that can be co-produced alongside 2G ethanol within a biorefinery. It is feasible to implement a distinct approach for certain new products, involving the direct conversion of a portion of the carbohydrates to produce them. Although this strategy might lead to a reduction in ethanol production, these novel products typically possess a higher value. As a result, they hold the potential to substantially enhance the economic viability of the facilities. Examples of such products include bio-pigments, biopolymers, xylitol, and biohydrogen. In the context of valorizing side-streams, studies have explored the production of chemical building blocks, biosurfactants, xylitol, biogas, and lignin derivatives. Notably, many of these studies have not incorporated a techno-economic assessment approach, thereby highlighting the promising opportunity for conducting new simulation and TEA studies.

Author Contributions: All authors contributed to the methodology and conceptualization of the review. V.P.S., L.R., M.M.C.-S., C.A.P., F.M.J. and G.L.d.A. carried out the literature research and drafted the original paper. S.S.d.S., S.I.M. and J.C.d.S. directed the literature research and edited the original draft. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Novo Nordisk Foundation (NNF), Denmark (grant number: NNF20SA0066233), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Brazil (Finance code 001), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Brazil (grant number: 305416/2021-9), and Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Brazil (grant number: #2020/12059-3).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Declaration of AI and AI-Assisted Technologies in the Writing Process : During the preparation of this work the authors used the free version of CHATGPT (provided by OpenAI, San Francisco, California, U.S.; available at https://openai.com/blog/chatgpt) in order to partially aid with the language edition. Afterwards, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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