Barriers to the adoption of the circular economy in the Brazilian sugarcane ethanol sector

Gessica Mina Kim Jesus1 · Daniel Jugend1 · Luis Alberto Bertolucci Paes1 · Regiane Máximo Siqueira1 · Matheus Artioli Leandrin1

Received: 12 January 2021 / Accepted: 29 May 2021 / Published online: 4 June 2021
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2021

Abstract
Brazil plays a prominent role in the global production of sugarcane and contributes to the renewable energy sector by producing ethanol. However, few studies have explored the adoption of the circular economy in the sugarcane ethanol sector. This article is aimed at analyzing and prioritizing barriers to the adoption of the circular economy in leading Brazilian sugarcane ethanol companies. For this, the analytical hierarchy process method and case studies methods were used. The main barriers identified were economic and financial, mainly due to dependence on high investments in production process technologies and the resulting uncertainties about returns. Another barrier was the lack of Brazilian legislation concerning the circular economy. We discuss the implications of our findings and present mechanisms for overcoming barriers and the role in supporting circular economy adoption in emerging economies.

Graphic abstract

Extended author information available on the last page of the article
Keywords Bioeconomy · Developing countries · Sustainable design · Bioethanol · Multi-criteria decision analysis

Introduction

Interest in the circular economy (CE) has grown in recent years, as seen in the efforts of some of the major world economies to incorporate its principles into advancing their sustainable development strategies (Ranta et al. 2018). There is also growing interest in academic research, as well as that conducted by practitioners and companies interested in investigating or applying the CE (Kirchherr et al. 2018). CE principles involve ends such as narrower, slower and closed end-of-pipe technologies, energy and material loops, through sharing, reduction, reuse, recycling and recovery in the production, distribution and consumption processes (Geissdoerfer et al. 2017).

The transition from a linear economy to a CE requires effort to manage the necessary organizational changes, as well as improvements in process technologies and products (Bocken et al. 2016; Jesus and Mendonça 2018). For example, the cost of virgin raw materials is often lower than that of recycled or remanufactured materials, and there can be economic issues and from the perspective of companies in adopting a CE (Kirchherr et al. 2018). There may therefore be resistance to deviating from the technological and cultural standards linked to linearity, as economic, technological, market and organizational factors are involved (Jesus and Mendonça 2018; Jabbour et al. 2020).

Despite the importance of renewable energy generation to CE adoption, little is known about the relationship between barriers to CE adoption and renewable energy production (Sawhney 2020), especially in developing countries. There is a need to expand scientific research in this area through empirical studies that provide data and reliable strategies, as little research has focused on CE and its barriers. Meeting the excessive demand for energy using current resources and conventional economic models remains an unsustainable process, mainly because many industries in the linear economy have been environmentally aggressive in their use of natural non-renewable resources (Peterson 2017).

Renewable energy is a viable alternative to the depletion of fossil fuels (Kapoor et al. 2020), and the cycles of materials proposed by the CE will only be effectively closed when the energy used is also renewable (Desing et al. 2019). Renewable energy sources are considered clean and environmentally friendly (Kibaara et al. 2020). From this perspective, technology and ecology can have a positive influence on energy companies’ strategic decisions (Borowski 2020; Trung, 2020). Using solar systems with photovoltaic technologies (Kibaara et al. 2020) and lignocellulose biomass for ethanol and electricity production (Galanopoulos et al. 2020) can support the transition to a CE. Perception of innovation through enabling technologies is critical to solutions based on renewable energy systems (Consuelo 2020). In addition to reducing costs, renewable energy sources can also reduce CO2 emissions (Qerimi et al. 2020).

Brazil is responsible for about 41% of the world’s sugarcane production (Silalertruksa and Gheewala 2020; Meghana and Shastri 2020). This facilitates the production of ethanol and energy from the lignocellulose biomass from sugarcane (Meghana and Shastri 2020). This is an attractive alternative that can reduce dependence on fossil fuels (Galanopoulos et al. 2020; Giuliano et al. 2019). However, lignocellulose biomass valorization through 2nd-generation bioethanol should account for its integration with territories and other productive chains (Galanopoulos et al. 2020). This can be accomplished by simulating the locations, production and demand of biorefineries to minimize the costs associated with these processes (Galanopoulos et al. 2020).

Ethanol is widely accepted in Brazil and its automobile market, and the country’s government—at least in the past three decades—has encouraged the development and production of engines compatible with biofuel technology (Maroun and La Rovere 2014; Ferrari et al. 2019), as well as car engines that can use either ethanol or gasoline. Currently, the Brazilian government encourages the use of biofuels in the country through the RenovaBio Program. Furthermore, a recent project in Brazil has integrated automakers with the sugarcane ethanol sector for the use of ethanol in hybrid cars (Silva 2020).

Given that little is known about the adoption of the CE in the sugarcane ethanol sector, particularly for the development and production of renewable energies, this article is aimed at (i) identifying and analyzing the main barriers to CE adoption in companies in the sugarcane ethanol sector and (ii) proposing ways to overcome these barriers. Moreover, this study is aimed at answering the following research questions, which require further clarification: What are the main barriers to the adoption of the CE in the Brazilian sugarcane ethanol sector? How should these barriers be prioritized in the development of new strategies for sustainable operations for this sector?

To answer these questions, we conducted a case study of two of Brazil’s largest sugarcane plants and analyzed and prioritized the barriers using the analytic hierarchy process (AHP). In addition to investigating the barriers to CE adoption in the sugarcane ethanol sector for the production of renewable energies, this article is novel in its adoption of the AHP method with case studies using a mixed research approach and with qualitative and quantitative elements to analyze these barriers. Despite the large number of studies on the CE, as far as we are aware, none has investigated CE
Barriers in the renewable energy sector, especially using the AHP method. In the recent literature, we observed that the AHP has been applied in studies aimed at prioritizing CE barriers in other situations, such as in India’s manufacturing (Kumar et al. 2021) and mining (Singh et al. 2020) sectors. Moreover, emerging countries have received little attention regarding the CE (Agyemang et al. 2019), and further research in this field is relevant, considering the reality of these countries (Jabbour et al. 2020).

This article is organized into six sections. Section 1 presents the introduction with the paper’s research questions and objectives. Section 2 presents the review of the literature related to CE and the main barriers to CE adoption. Section 3 details the research method. Section 4 presents the results of AHP and case studies. Section 5 discusses the barriers to CE adoption, the ways to overcome them and limitations and future research. Finally, Sect. 6 presents the conclusion of the paper.

The circular economy and its barriers

The CE has been proposed as an alternative to the linear economy (Jesus and Mendonça 2018). Whereas the linear economy presupposes an economic model based on the activities of extraction, transformation and disposal of products and materials, the CE focuses on the restoration and regeneration of products and materials (Ellen MacArthur Foundation, 2015). Geissdoerfer et al. (2017, p. 759) define CE “as a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops.” For Kirchherr et al. (2018), the CE can be understood as a business model that replaces the concept of end-of-life by reusing, recycling and recovering materials in the processes of production, distribution and consumption.

The CE aims to maintain products, components and materials at their highest level of usefulness and value as long as possible by closing technical and biological cycles (Bocken et al. 2016). The technical cycle involves strategies for the recovery and restoration of materials, whereas the biological cycle manages the flow of renewable materials to facilitate the regeneration of renewable (i.e., biological nutrients) (Ellen MacArthur Foundation, 2015).

Although the transition from a linear economy to a CE is not an easy path, several factors have motivated this transition, such as the need to avoid the degradation and depletion of natural resources, the increase in government regulation, advances in clean technologies and urban population growth (Geissdoerfer et al. 2017). Moreover, this transition requires that business models align with its principles (Jaeger and Upadhyay 2020; Kirchherr et al. 2018), which should include environmental and societal interests (Geissdoerfer et al. 2017).

In the circular business model, resources, abilities and activities are aimed at providing a value proposition that offers benefits to customers through products and services that maximize resource efficiency (Bocken et al. 2016). Most products that would have been disposed of in the linear model are reused by, for example, turning them into other products. The shift to a CE can require radical changes in production and consumption (Ritzen and Sandström 2017). In this sense, stakeholders can influence how firms deal with barriers to and motivators for CE adoption (Jabbour et al. 2020).

The barriers and challenges of moving from a linear to a circular model have been widely recognized and discussed in the recent CE literature (e.g., Ritzén and Sandström 2017; Kirchherr et al. 2018; Agyemang et al. 2019). These barriers involve a product’s life cycle and the entire supply chain from design to new product development (Bocken et al. 2016), as well as energy sources (Kumar et al. 2021), production, distribution and consumption (Jesus and Mendonça 2018).

In this context, Ritzén and Sandström (2017) identified the main barriers as (i) financial: difficulties in measuring the economic benefits of CE and doubts about its financial profitability and period of return on the investment required, (ii) structural: lack of clarity about the responsibilities of the different departments of a company involved in the adoption of the CE, (iii) operational: the role of companies in the supply chain adopting the CE and the way to sell and distribute their products, which includes reliance on suppliers for the adoption of the CE and (iv) attitudinal: company resistance to adopting circular business models. In addition, because CE is a new area, employees might have little understanding of its meaning, leading to technological implications for changes in products and production processes and impacts of these changes on company costs (Ritzen and Sandström, 2017).

Similarly, Shahbazi et al. (2016) identified the following barriers to the adoption of environmental strategies: (i) limited financial capacity, (ii) lack of information, (iii) market and environmental results and uncertainty benefits, (iv) lack of commitment from top management, (v) lack of clarity regarding strategic and business objectives, (vi) little awareness and qualification among employees and (vii) lack of scarcity of technology and equipment.

Kirchherr et al. (2018) conducted interviews with CE experts in the European Union and concluded that the cultural barriers, particularly the lack of interest and consumer awareness, and lack of an organizational culture in companies were the major difficulties affecting the adoption of the CE. In Europe, the so-called Not in My Back Yard (NIMBY Syndrome) is a social and environmental barrier because the
population is opposed to biomass combustion plants due to atmospheric pollution (Giuliano et al. 2018).

Jaeger and Upadhyay (2020) identified the main barriers to the CE adoption as the high cost of implementation processes, the complexity of supply chains, the challenges to cooperation and coordination between companies, lack of information on product design and production, lack of technical skills, fear of losing the quality performance of materials and the cost and time required for product disassembly.

When analyzing the management of bio-waste through the CE, Kapoor et al. (2020) identified technical (lack of knowledge in the supply chain, cost of technology, already consolidated models of energy waste), financial (high cost of technologies, lack of subsidies for the use of biogas) and institutional and regulatory (lack of coordination and cooperation with public policymakers and lack of adequate policies) barriers. Paes et al. (2019) found that the main barriers to the development of the circular bioeconomy are related to cultural issues, mainly people’s lack of knowledge about the topic, especially among agricultural producers who work in an important context with great potential for the reuse of agricultural waste.

An extensive literature review identified the main barriers relevant to the scope of this research. Table 1 summarizes these barriers and classifies them into social and environmental, economic and financial, and technological and operational categories. A brief description of each barrier is presented, as well as its theoretical framework.

### Research method

For this study, we adopted the mixed research approach with qualitative and quantitative elements (case studies and AHP analysis, respectively). The central assumption justifying this integrated approach is that the interaction between the approaches offers better and deeper possibilities for analysis (Creswell and Clark 2017). The first research step was to establish the main barriers to the adoption of the CE, accounting for the theoretical results presented in this article. The second research step was conducting the case studies. This form of research facilitates the analysis of a smaller number of scenarios and emphasizes a clear understanding of the phenomenon studied (Yin, 2003). The exploratory approach is also suitable for our research, as it deals with a new and emerging field of knowledge: barriers to CE adoption in the sugarcane ethanol sector.

Two companies were selected that represent a range of different possibilities for the production of renewable energy, which is a key sector for the development of the CE in a country with strong potential for expansion into new niches, as the generation of renewable energy can enhance CE in different industrial sectors. The two selected companies have the following common characteristics: (i) they are large-scale Brazilian companies operating in the sugarcane ethanol sector; (ii) they have diversified bioenergy portfolios; and (iii) the three main products offered by the companies are sugar, alcohol and energy. Company B, for example, is a leader in the generation of electricity from Brazilian sugarcane bagasse and has a network of 26 agro-industrial units. Table 2 presents an overview of the companies.

After initial contact, we collected the data through questionnaires with open questions, mainly about the CE practices in the companies and their main barriers. In addition to formal interviews, informal conversations about sustainable development projects and entrepreneurial policies were held to deepen knowledge about barriers to the adoption of the CE in the companies.

The third research step was to use the AHP analysis to examine and prioritize data for the barriers identified in the case studies. The AHP is widely used for multiple criteria decision-making in complex environments and organizes factors into a hierarchical structure comprising the goal, criteria, sub-criteria and alternatives in the process of decision-making (Saaty 1990), providing decision-makers with the capacity of objective measures.

The AHP analysis was fundamental to facilitating the structuring of the problem because it is a consolidated method widely used to prioritize barriers, and its analysis structures were applied in important and recent studies in environmental sustainability (e.g., Sharma et al 2020; Kumar et al. 2021; Bhandari et al. 2019). In addition, it is an intuitive and easy-to-understand tool for researchers and others involved in decision-making. In addition, decision-makers usually choose the methods and tools they will use to handle the process in order to balance the necessary effort and the desired precision in the process (De Almeida et al. 2015). In cases where greater involvement by decision-makers is possible, other methods can be used, such as MACBETH and MAUT. Figure 1 shows the steps followed in the research method.

We applied the AHP using the four phases proposed by Bhandari et al. (2019):

1. Organization of the problem and structuring of the AHP model. This initial phase includes the formulation of the hierarchy, representing the goal, strategic areas and sub-factors. The goal is positioned at the first level of the hierarchical structure. Three categories of barriers form the second level of the hierarchy (i.e., socio-environmental; economic and financial; technological and operational). The third level of the hierarchy consists of the 10 barriers that were proposed by the research (see Table 1).

2. Measurement and data collection. Experts make their judgments by answering questions comparing two cat-
| Categories                          | Barriers                                      | Code | Description                                                                                     | Reference                                                                                      |
|------------------------------------|-----------------------------------------------|------|-------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| Social and environmental           | Lack of awareness of CE principles            | BS1  | Society does not yet know the principles of the CE. We still need to develop education and culture aimed at protecting and preserving the environment | Jesus and Mendonça (2018), Kirchherr et al. (2018), Kumar et al. (2019), Agyemang et al. (2018), Bhandari et al. (2019) |
|                                    | Low demand for reused, remanufactured and shared products | BS2  | The market has not presented a clear demand for reused, remanufactured, recycled and shared products | Ritzén and Sandström (2017), Jesus and Mendonça (2018), Kirchherr et al. (2018), Ranta et al. (2018), Kumar et al. (2019) |
|                                    | Lack of regulation and legislation            | BS3  | The lack of specific legislation for the CE hinders the adoption of circular practices, as it reflects the absence of regulatory pressure and instruments | Jesus and Mendonça (2018), Kirchherr et al. (2018), Ranta et al. (2018), Bhandari et al. (2019), Shahbazi et al. (2016), Jabbour et al. (2020), Kapoor et al. (2020) |
| Economic and financial             | Lack of financial support and tax incentives  | BEF1 | The lack of financial support and tax incentives discourages investments in the CE, which has high initial costs | Jesus and Mendonça (2018), Kirchherr et al. (2018), Bhandari et al. (2019), Kumar et al. (2019), Jaeger and Upadhay (2020), Jabbour et al. (2020) |
|                                    | Low cost of virgin materials                  | BEF2 | The cost of products and components as virgin materials is usually less than the cost of used products and components (e.g., remanufactured and recycled materials) | Kirchherr et al. (2018), Kumar et al. (2019), Shahbazi et al. (2016) |
|                                    | High cost of CE processes                     | BEF3 | The high cost associated with CE processes prevents their adoption in the manufacturing sector (e.g., disassembly, remanufacturing and product recycling processes) | Ritzén and Sandström (2017), Agyemang et al. (2018), Jesus and Mendonça (2018), Kirchherr et al. (2018), Ranta et al. (2018), Jaeger and Upadhay (2020), Jabbour et al. (2020) |
| Technological and operational      | Lack of technology and equipment              | BTO1 | The technologies and equipment are insufficient to support the manufacture of products that meet the principles of the CE | Ritzén and Sandström (2017), Jesus and Mendonça (2018), Kirchherr et al. (2018), Bhandari et al. (2019), Kumar et al. (2019), Shahbazi et al. (2016), Kapoor et al. (2020), Jabbour et al. (2020) |
|                                    | Lack of qualified labor                       | BTO2 | The available labor force does not have the qualifications or experience for the operationalization of the CE | Ritzén and Sandström (2017), Jesus and Mendonça (2018), Bhandari et al. (2019), Kumar et al (2019), Jaeger and Upadhay (2020), Shahbazi et al. (2016), Kapoor et al. (2020), Jabbour et al. (2020) |
|                                    | Lack of design and production information    | BTO3 | Design and production information is insufficient to support the manufacture of products that meet the principles of the CE (e.g., it is unclear how a product’s life span can be extended) | Jesus and Mendonça (2018), Kirchherr et al. (2018), Jaeger and Upadhay (2020), Shahbazi et al. (2016), Jabbour et al. (2020) |
|                                    | Difficulty establishing partnerships in the supply chain | BTO4 | Participants in the supply chain (e.g., suppliers and customers) do not share environmental concerns, making it difficult to establish partnerships for the manufacture of products that meet the principles of the CE | Ritzén and Sandström (2017), Jesus and Mendonça (2018), Jaeger and Upadhay (2020), Shahbazi et al. (2016), Kapoor et al. (2020), Jabbour et al. (2020) |
categories at a time, and barriers considering their relationships, using the Saaty scale (Saaty, 1990). To this end, four experts were consulted to answer the AHP questionnaire: three from Company A and one from Company B. Company A’s experts agreed to deliver only one questionnaire. Two experts from Company A occupy the position of environmental preservation analysts, one with 21 years of experience and another with 11 months of experience in the sector. The third expert from Company A is a maintenance supervisor with 11 years of experience in the sector. The expert from Company B is an operations management analyst and has 2 years of experience in the sector.

3. Determination of standardized weights. In this phase, the judgment matrices for the paired comparisons obtained in the previous phase were formed and the relative importance of the categories and barriers were calculated according to the AHP. Inconsistencies in the answers provided by the decision-makers were also analyzed, which, according to Saaty (1990) should not exceed 10%.

4. Definition of the solution to the problem.

We also carried out a sensitivity analysis because this method allowed us to assess the stability of the global barrier weights in decision-making. Using sensitivity analysis, alternative scenarios can be created by increasing or decreasing the weights of the categories, directly affecting the decision-making results (Delmonico et al. 2018). Super Decisions version 2.10 (Creative Decisions Foundation 2000) software was used to model and apply the method described in this section. This was done to support decision-makers in identifying the priority of alternatives for each category in this analysis and the consistency of the matrix decision associated with the answer to a question. Figure 2 illustrates the goals, categories for and barriers to analysis in this research.
**Results**

**Company A**

Company A has operated in the sugarcane ethanol sector since 1946, producing sugar, ethanol and energy in Brazil and exporting part of its production. With three agro-industrial units and 3,500 employees, the company crushed 10.8 million tons of sugarcane during the 2019/2020 harvest. All sugar and ethanol production passes through the largest Brazilian sugar and ethanol cooperative, which is an important exporter in the global market. This cooperative is responsible for the connection between plants and the customer, as it sells products on a large scale while carrying out a logistical operation with the capacity to integrate all stakeholders into the value chain. The company has RenovaBio certification, an initiative by the Brazilian government to increase the presence of ethanol and other biofuels in Brazil’s energy matrix. The RenovaBio Program became effective in Brazil in 2019 due to the decarbonization goal in the 2015 Paris Agreement. Furthermore, fuel distributors have to achieve decarbonization goals through the acquisition of decarbonization credits (CBIOs) to prove their reduction of CO2 emissions.

The main CE practices observed in Company A are based on the waste hierarchy (Pires and Martinho 2019) and the regeneration of natural systems (Wohlfahrt et al. 2019) through the reuse of waste such as vinasse, biomass, cane trash and press mud. Spent washer or vinasse is a rich source of potassium and, combined with commercial fertilizer, reduces fertigation costs. According to one of the interviewees, “Today we use vinasse for fertigation and irrigation, but in the future, we are also planning to use vinasse for the production of electric energy through a biodigester in the generation of biogas.”

Biomass is the company’s main feedstock for electricity generation. According to environmental preservation analysts: “Sugarcane biomass is a renewable source used to generate electricity that supplies 100% of our plant, we export the surplus generation to neighboring cities.”

Cane trash is either utilized to prevent soil erosion or combined with biomass for electricity generation. As reported in the case study, “In the past, cane trash was burned, but today, burnt cane harvest is prohibited, so we have to rethink a more suitable destination. With 100% mechanized harvests, we leave a half of cane trash in the soil to prevent erosion and the rest is incorporated into the biomass process.”

Sugarcane press mud is a dark brownish residue obtained during the clarification and filtration of cane juice; it is utilized as compost for fertilization due to nitrogen levels. Water is an important input to the sugar mill process that gives rise to issues such as waste and reutilization. There is a substructure capable of cooling the water, allowing for its reuse along the process. Equally important, predictive maintenance is key to avoiding failure and overloading the equipment. According to the maintenance supervisor: “Predictive maintenance was adopted for this sugar mill, we only change
parts and equipment after its performance evaluation, this avoids the premature exchange of parts and the unnecessary consumption of electricity or inputs, for example."

Three main incentives for CE adoption were highlighted at the company: (i) customers have demanded more sustainable solutions; (ii) the local community pushed to reduced pollution from factories in the region; and (iii) top management, in addition to aiming to improve the sustainability of operations, also understands that the CE encourages less use and waste of resources and that this tends to improve financial performance. On the other hand, the interviewees noted the lack of public policies and the high cost of technologies required by the CE as factors that discourage its adoption:

- Lack of public policies: “In Brazil, there is a lack of public policies that encourage the practices of the CE, such as the reduction of taxes.”
- High cost of new technologies: “There is technology for implementing projects, but it is expensive. This directly affects the payback process. Projects with delayed payback, over 48 months, are rejected by the board.”

**Company B**

Company B is a multinational joint venture between a Brazilian and a Dutch company. The joint venture was made official in 2010. Company B produces sugar, ethanol and bioenergy besides being active in the logistics and commercial sectors with an integrated distribution system around Brazil. The company has offices in Switzerland, the Philippines, Singapore, the United States and Brazil. It has more than 26 producing units, 67 distribution terminals and approximately 30,000 employees in Brazil. According to data provided by the company, in 2020, it crushed approximately 61.4 million tons of sugarcane.

Company B holds several certifications, including Bon-sucro, SMETA, EPA (United States), ISCC (Europe), METI (Japan), the International REC Standard and California Air Resource Board and RenovaBio. The company, which is self-sufficient, has a wide portfolio of electric energy technologies that use renewable sources, such as biomass, sugarcane straw, biogas and photovoltaic energy. The energy produced during the years 2019 and 2020 was able to reach the consumption of all 26 agro-industrial units and allowed the surplus production to be traded to other companies and the energy sector. In 2020, the company inaugurated its first solar-powered unit, and by 2021, it should complete the construction of a biogas-powered unit.

The company was also noted as a leader in the production of energy generated from bio-waste sugarcane in Brazil. According to the company’s operations management analyst:

“Our bioenergy production is capable of supplying the city of Rio de Janeiro for one year in a constant and predictable way, and the peak of our production and generation of electricity is specifically the driest period of the year when the water matrix is under more pressure.”

Biomass is the company’s main source of renewable energy production. Biogas is produced by biodigesters that convert the organic matter from the processing of sugarcane (e.g., filter cake, vinasse) into methane and CO2. Biogas is used in motor generators that transform it into clean electrical energy. “In 2018, we started the construction of a biogas plant to increase our capacity to generate electricity at the plant by 40%.” The company also uses solar energy as a source of renewable energy:

“In a step towards the future, we developed the largest solar energy plant in the state of São Paulo with an installed capacity of 1.3 MWp. With the plant, we have reached a new level of innovation, which represents the search for more sustainable energy management, based on clean, perennial and economical energy.”

There are two main incentives for the company to adopt CE. The first is pressure from members of top management, who are considering the possible financial benefits of optimizing and reusing the materials produced by the company, especially sugarcane bio-waste, as well as improving environmental performance and market gains related to the company’s sustainability image. The second is the pressure from stakeholders in the supply chain (e.g., the beverage sector), who have greater environmental responsibility regarding their suppliers.

Company B’s CE practices are mainly focused on the reuse of all sugarcane residues for power generation and other products (e.g., sugarcane bagasse pellets). An interviewee noted that “even after the processing of sugarcane, the bagasse generated is transformed into biomass for energy generation.” Moreover “the sugarcane press mud is used as a fertilizer, which is then used in the fields.”

Barriers noted to the adoption of the CE included the high investment required for the acquisition of new technologies and the changes required in the production processes of the company’s various units. If the return on this investment is uncertain, it is also likely that members of top management may oppose CE-related projects, which is another barrier to adoption. Ethanol was also noted as well accepted in the Brazilian automobile market, and it has been supported by the Brazilian government since the 1980s. There is a lack of international demand for this product, however, which is an obstacle. Ethanol demand from the international automobile market would probably drive greater investment in resources for CE projects.
Prioritization of barriers through the application of AHP

After structuring the AHP model (Fig. 2), experts from Companies A and B in the sugarcane ethanol sector completed the judgment matrices for the categories and barriers using the values of Saaty’s (1990) scale as a reference. We calculated the relative importance of the categories and barriers with the support of the Super Decisions software. Tables 3 and 4 present the results of the weights assigned to each category by Company A and B, respectively. The analyzed categories were social and environmental, economic and financial, and technological and operational.

For Company A, the economic and financial category represents the vast majority (75.1%) of all barriers, compared to the social and environmental (17.1%) and technological and operational (7.8%) categories. For Company B, economic and financial matters represent the vast majority of barriers (78.5%) compared to the technological and operational (14.9%) and social and environmental (6.6%) categories. In both companies, the economic and financial category exceeded 75%, making it a candidate for the most critical category. Results differed for other categories (i.e., social and environmental, economic and financial, and technological and operational).

Regarding the prioritization of the ten selected barriers, Table 5 shows the local and global weights indicated in the AHP analysis for Companies A and B (the meaning of the abbreviations used in Table 5 can be found in Table 1).

In relation to local weights, the lack of regulatory pressure and instruments (BS3) was the most significant within the social and environmental category for both companies. In the technological and operational category, the lack of technology and equipment (BTO1) was also the most significant for both companies. In the economic and financial category, the lack of financial support and tax incentives (BEF1) was more significant for Company A, whereas the high cost of CE processes (BEF3) was the most significant for Company B.

Regarding the global weights for Company A, the lack of financial support and tax incentives topped the rankings with the highest weight (BEF1: 55%), whereas the lack of qualified labor had the lowest overall weight (BTO2: 5%). For Company B, the global weight of the high cost of CE processes was the largest (BEF3: 58.9%), whereas the global weight of the low demand for reused, remanufactured and shared products was the smallest (BS2: 4%). To facilitate the comparison of the barriers prioritized by Companies A and B, Fig. 3 illustrates the global ranking of barriers according to the degree of importance as indicated by the companies’ AHP.
According to Fig. 3, the three most significant barriers identified for Company A were the lack of financial support and tax incentives (BEF1: 55%), high cost of CE processes (BEF3: 15%) and lack of regulatory pressure and instruments (BS3: 12.1%). For Company B, the three barriers with the highest weights were the high cost of CE processes (BEF3: 58.9%), the low cost of virgin materials (BEF2: 13.5%) and insufficient technologies and equipment to support the manufacture of environmentally sustainable products (BTO1: 9%).

To investigate the implications for the companies if the economic and financial barriers were less significant, we carried out a sensitivity analysis for this category. We chose this category because it was the most significant for both companies. The weight of economic and financial barriers ranged from 10 to 90% to test the barriers’ final classification. This range of variation was based on the study by Delmonico et al. (2019). Figures 4 and 5 show the behavior of the barriers when the weight of the economic and financial barriers category varies for Companies A and B, respectively.

Although the economic and financial category is the most significant for the two companies, the sensitivity analysis provided different results for them. For Company A, Fig. 4...
Barriers to the adoption of the circular economy in the Brazilian sugarcane ethanol sector

indicates that when the weight of the economic and financial barriers category is 10%, socio-environmental barriers are the main issues related to CE adoption, as exemplified by the lack of pressure and regulatory instruments (BS3: 41.4%), and lack of awareness about CE principles (BS1: 10.4%). Because the weights in the category of economic and financial barriers are greater than 30%, the lack of financial support and fiscal incentives becomes the most important barrier (BEF1: 33%). Finally, when the weight of the economic and financial category reaches 50%, the barrier posed by the high cost of CE processes is more intense (BEF3: 14.9%) than the lack of pressure and regulatory instruments (BS3: 12.1%).

For Company B, Fig. 5 shows a different result because if the weight of the category of economic–financial barriers were 10%, technological and operational issues would be the main barriers to the adoption of the CE, as exemplified by the lack of technology and equipment (BTO1: 35.3%) and difficulty in establishing partnerships in the supply chain (BTO4: 9.7%). When the weight of the economic and financial category reaches 30%, however, the barrier posed by the high cost of CE processes (BEF3: 35.4%) is more intense than is the lack of technology and equipment (BTO1: 22.2%). Socio-environmental barriers are practically zero for weights in the economic–financial category above 60%. Therefore, the results of the sensitivity analysis reinforce the results of prioritizing barriers obtained by the AHP.

Discussion

Barriers to the adoption of the circular economy

Ethanol is a viable option that can decrease greenhouse gas emissions by up to 85% by replacing fossil fuels (Börjesson 2009). It can also facilitate the use of bio-waste as a secondary energy source (Meghana and Shastri 2020; Silalertruksa and Gheewala 2020). However, the transition to renewable energy requires many innovations and various technologies to compete with fossil fuel technologies (Neto and Gallo 2021). For companies that use commodities as raw materials, the reuse of bio-waste in line with the CE approach involves many uncertainties, particularly if the raw material is seasonal. Variables such as climate change and rising production costs mean that operations management aims to balance risk management, operations and crop optimization (Paes et al. 2019; Wohlfahrt et al. 2019).

Due to its economic and environmental importance, especially with regard to the generation of renewable energy, the sugarcane ethanol sector can play a prominent role in the transition from the linear economy to the CE in Brazil. Thus, it is important to know the main barriers this transition faces. Our results fill a research gap that has not been investigated previously: the transition from the linear economy to the CE in renewable energy-producing sectors (in this study, by companies in the sugarcane ethanol sector). The main barriers identified in order of priority were as follows:

1. Lack of financial support. Our results indicate the lack of financial support for the adoption of the CE. Unlike the European Union, which has financing programs to support the transition to a CE, such as the European Structural and Investment Funds, Horizon 2020 and the LIFE program, Brazil does not yet have mature public policies that encourage CE adoption.
2. High costs associated with CE. The companies studied showed that they depend on investments in technologies to develop their current CE projects, such as bioenergy, biogas and solar energy. When investigating other emerging countries, Bhandari et al. (2019) noted that
financial institutions have not supported the development of clean technologies. Companies in Brazil seeking to adopt the CE approach may face similar difficulties, making economic and financial barriers more difficult to overcome. The high costs of investments and the uncertainty of returns proved to be relevant barriers for CE adoption for these sugarcane ethanol companies in Brazil. The complexity of implementing the CE principles includes new technologies, infrastructure, organizational cultural change, learning curves and investments in knowledge. In addition to the economic and financial barriers, the high costs of processes involved in adhering to CE principles, such as recycling, reuse, remanufacturing and the alteration of the factory layouts, were identified as barriers and were highlighted mainly by Company B.

3. Lack of CE-specific legislation. In addition to our quantitative results, the companies indicated that Brazil lacked public policies that encourage the adoption of CE practices, such as tax breaks for companies aligned with circularity. Unlike the European Union and China, there is still no specific legislation for the CE in Brazil, despite solid waste legislation (Sousa Jabbour et al. 2014). Our findings on the lack of CE-specific legislation are in line with other results in Brazilian studies on eco-design (Jugend et al. 2017), innovative business models (Jabbour et al. 2020) and solid waste management (Guarnieri et al. 2020; Lima et al. 2018). A significant milestone for Brazil in moving toward the CE in terms of national policy was the RenovaBio Program’s consolidation and alignment with the decarbonization target set in the Paris Agreement in 2015. Fuel distributors can thus meet decarbonization goals through the acquisition of CBIOs, certificates issued by biofuel producers that prove the reduction of CO2 emissions through an efficient and environmentally responsible production process.

It is important to note that, for both companies, which operate in the same political, economic, social, environmental and technological context, financial barriers were the most important. Company A lacked financial support, and Company B faced high processing costs related to CE (which was also the second most important barrier observed by Company A). This result differed from those found by studies in other countries and industrial sectors. For example, in the European Union, cultural barriers such as a lack of interest in getting involved with the CE were significant (Kirchherr et al. 2018). In Pakistan, a lack of awareness and a lack of expertise were barriers to implementing CE principles in the automobile industry (Agyemang et al. 2019). In India, the lack of a skilled workforce, an ineffective performance framework and short-term goals and ineffective organization strategies were the main barriers to CE adoption in the manufacturing sector (Kumar et al. 2021). Barriers such as a lack of qualified labor and design difficulties, which were observed in other studies (e.g., Kirchherr et al. 2018; Jaeger and Upadhyay 2020), did not stand out in our results as relevant barriers (Fig. 3). This result can be explained by the fact that the companies we investigated were involved with the processing of commodities and were therefore more involved with process innovation than product innovation.

Ways to overcome these barriers

The main barriers to transitioning to the CE identified in our study were economic and financial (75.1% in Company A and 78.5% in Company B). Considering these barriers, the high manufacturing costs associated with the adoption of CE were highlighted in this study’s quantitative and qualitative phases, primarily because the transition to the CE in the sugarcane ethanol sector depends largely on investments in process innovation. These barriers can be overcome by strengthening partnerships with various stakeholders present in this ecosystem (e.g., suppliers, customers, universities, cooperatives) through the sharing of R&D infrastructure and jointly developed projects in areas such as bioenergy, biogas and the reuse of bio-waste. Furthermore, public policy makers in the environmental and innovation fields could also stimulate and coordinate these stakeholders’ roles, to generate economies of scale and decrease the cost of investing in new technologies aimed at transitioning to the CE. Tax and regulatory incentives in Brazil’s renewable energy sector could also help overcome these barriers, because the lack of stimuli in public policies is another relevant difficulty in this sector concerning the transition to the CE.

The sensitivity analysis results also indicated that the weight variation of the economic and financial barrier category has different implications for the two companies. If financial and economic difficulties were resolved or mitigated in Company A, the next step would be to direct efforts toward overcoming socioeconomic barriers. These barriers are related to legislation aimed at regulating the adoption of the CE. If financial and economic difficulties were resolved or mitigated in Company B, the next step would be to overcome its technological barriers.

Limitations and future research

We recognize that this study has limitations that deserve consideration. First, even considering that the companies investigated are prominent players in the Brazilian sugarcane ethanol sector, the limitations of the research method we employed mean that the results presented here cannot be generalized. For example, although economic and financial barriers have been highlighted in this study, our findings
reflected the results obtained through the AHP method and case studies in only two companies, operating in Brazil. We suggest, therefore, that future studies investigate, through a wider sample of companies from different countries, whether financial and economic barriers are the most important in the renewable energy sector. Secondly, the case studies focused on the perspective of specialists in the sector, without accounting for the views of different actors in society. Future studies could use focus group research with different experts from the sugarcane ethanol sector to identify other and new barriers to CE adoption.

Regarding our results and the possibility of adopting CE in sectors such as the sugarcane ethanol sector or those that produce renewable energy, future studies could investigate:

1. Mechanisms that could drive circular supply chains, identifying and proposing practices for industrial symbiosis between farmers, producers and distributors of the sugarcane energy sector.
2. How the expansion of the energy network of a country or region can contribute to the adoption of the CE at macro-, meso- and micro-levels.
3. Public policies that encourage the closure of biological cycles of the CE and that value agricultural waste.
4. Means of coordination and collaboration between different circular ecosystems sectors (e.g., producers, clients, suppliers, universities) for the development of CE-driven innovation.
5. Circular business models that consider the characteristics of renewable fuel production companies.

Conclusions

This study’s results contribute to the advancement of the field of knowledge in CE by presenting and analyzing its main barriers in the sugarcane ethanol sector. In addition to the results presented and discussed, the use of the AHP method integrated with case studies (a mixed approach to research involving qualitative and quantitative elements) for the analysis of these barriers is a methodological innovation of this study, as the existing literature still lacks this type of approach to the identification and analysis of barriers to CE adoption. The main barriers identified were economic and financial. Future studies could widen the understanding of the theme by investigating the barriers to the adoption of the CE in a greater number of renewable energy-producing companies (comparing cases in emerging and developed countries, for example), in addition to proposing ways of overcoming these barriers.

Acknowledgements The authors gratefully acknowledge the financial support of: (i) the Brazilian research funding agency CAPES, Coordination for the Improvement of Higher Education Personnel, Brazil (Grant 88887.605415/2021-00); (ii) the São Paulo Research Foundation. (FAPESP) Grant no. 18/23972-1

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

References

Agymen M, Kusi-Sarpong S, Khan SA, Mani V, Rehman ST, Kusi-Sarpong H (2019) Drivers and barriers to circular economy implementation: an explorative study in Pakistan’s automobile industry. Manag Decis 57(4):971–994. https://doi.org/10.1108/MD-11-2018-1178
Bhandari D, Singh RK, Garg SK (2019) Prioritisation and evaluation of barriers intensity for implementation of cleaner technologies: framework for sustainable production. Resour Conserv Recycl 146:156–167. https://doi.org/10.1016/j.resconrec.2019.02.038
Bocken NMP, De Pauw I, Bakker C, Van Der Grinten B (2016) Product design and business model strategies for a circular economy. J Ind Prod Eng 33:308–320. https://doi.org/10.1080/21681015.2016.1172124
Börjesson P (2009) Good or bad bioethanol from a greenhouse gas perspective - What determines this? Appl Energy 86(5):589–594. https://doi.org/10.1016/j.apenergy.2008.11.025
Borowski PF (2020) New technologies and innovative solutions in the development strategies of energy enterprises. HighTech and Innovation Journal 1(2):39–58
Consuelo N (2020) Advanced Design For Manufacturing of Integrated Sustainability Off-Shore and Off-Site Prototype-MVP S2_HOME. Civil Engineering Journal 6(9):1752–1764
Creswell JW, Clark VLP (2017) Designing and conducting mixed methods research. SAGE Publications.
De Almeida AT, Cavalcante CAV, Alencar MH, Ferreira RJ, de Almeida-Filho AT, Garcez TV (2015) Multicriteria and multi-objective models for risk, reliability and maintenance decision analysis. Springer International Publishing, Cham
Delmonico DVG, Santos HH, Pinheiro MAP, De Castro R, De Souza RM (2018) Waste management barriers in developing country hospitals: case study and AHP analysis. Waste Manage Res 36(1):48–58. https://doi.org/10.1177/0734242X17739972
Desing H, Widmer R, Beloin-Saint-Pierre D, Hirschier R, Wäger P (2019) Powering a sustainable and circular economy—an engineering approach to estimating renewable energy potentials within earth system boundaries. Energies 12(24):4723
Ellen MacArthur Foundation, McKinsey Center for Business and Environment. (2015) Growth within: a circular economy vision for a competitive Europe. Ellen MacArthur Foundation.
Ferrari AG, Scaliza JAA, Jugend D (2019) The landscape of open innovation in Brazil: an analysis of the recent literature. Production 29:1–10
Galanopoulos C, Giuliano A, Barletta D, Zondervan E (2020) An integrated methodology for the economic and environmental assessment of a biorefinery supply chain. Chem Eng Res Des 160:190–215
Geissdoerfer M, Savaget P, Bocken NMP, Hultink EJ (2017) The circular economy – a new sustainability paradigm? J Clean Prod 143:757–768. https://doi.org/10.1016/j.jclepro.2016.12.048
Giuliano A, Gioiella F, Sofia D, Lotrecchiano N (2018) A novel methodology and technology to promote the social acceptance
of biomass power plants avoiding nibby syndrome. Chemical Engineering Transactions, 67.

Giuliano A, De Bari I, Motola V, Pierro N, Giocoli A, Barletta D (2019) Techno-environmental assessment of two biorefinery systems to valorize the residual lignocellulosic biomass of the Basilicata region. Math Model Eng Prod 6:317–323

Guarnieri P, Cerqueira-Streit JA, Batista LC (2020) Reverse logistics and the sectoral agreement of packaging industry in Brazil towards a transition to circular economy. Resour Conserv Recycl 153:104541. https://doi.org/10.1016/j.resconrec.2019.104541

Jabbour CJ, Seuring S, de Sousa Jabbour ABL, Jugend D, Fiorini AS, (2019) Circular economy in the manufacturing sector: benefits, opportunities and barriers. Manag Decis 57(4):1067–1086

Kumar P, Singh RK, Kumar V (2021) Managing supply chains for circular economy: cases from the manufacturing industry. J Enterp Inf Manag 33(4):729–745. https://doi.org/10.1108/JEIM-02-2019-0047

Kumar V, Sezersan I, Garza-Reyes JA, de Sá MM (2020) Managing operations for circular economy in the mining sector: an analysis of barriers. Resources, Conservation and Recycling 164:105215

Kamba SK, Murage DK, Musau P, Saulo MJ (2020) Comparative analysis of implementation of solar PV systems using the advanced SPECA modelling tool and HOMER software: Kenyan scenario. HighTech and Innovation Journal 1(1):8–20

Kirkherr J, Piscicelli L, Bour R, Kostense-Smit E, Muller J, Huijbrechts-DeJong J, (2017) Environmental sustainability and product portfolio management in biodiversity firms: A comparative analysis between Portugal and Brazil. Contemp Econ 11(4):431–442

Kumar V, Ghosh P, Kumar M, Sengupta S, Gupta A, Kumar SS, Vijay V, Kumar V, Vijay VK, Pant D (2020) Valorization of agricultural waste for biogas based circular economy in India: a research outlook. Biores Technol. https://doi.org/10.1016/j.biortech.2020.123036

Kibaara SK, Murage DK, Musau P, Saulo MJ (2020) Comparative analysis of implementation of solar PV systems using the advanced SPECA modelling tool and HOMER software: Kenyan scenario. HighTech and Innovation Journal 1(1):8–20

Kumar V, Sezersan I, Garza-Reyes JA, Gonzalez ED, Moh’d Anwer AS, (2019) Circular economy in the manufacturing sector: benefits, opportunities and barriers. Manag Decis 57(4):1067–1086

Kumar P, Singh RK, Kumar V (2021) Managing supply chains for sustainable operations in the era of industry 4.5 and circular economy: analysis of barriers. Resources, Conservation and Recycling 164:105215

Lima PDM, Colvero DA, Gomes AP, Wenzel H, Schalch V, Cimpan C (2018) Environmental assessment of existing and alternative options for management of municipal solid waste in Brazil. Waste Manage 78:857–870. https://doi.org/10.1016/j.wasman.2018.07.007

Maroun MR, La Rovere EL (2014) Ethanol and food production by family smallholdings in rural Brazil: economic and socio-environmental analysis of micro distilleries in the State of Rio Grande do Sul. Biomass Bioenergy 63:140–155. https://doi.org/10.1016/j.biombioe.2014.02.023

Meghana M, Shastri Y (2020) Sustainable valorization of sugar industry waste: status, opportunities, and challenges. Biores Technol 303:122929. https://doi.org/10.1016/j.biortech.2020.122929

Neto IVS, Gallo WL (2021) Potential impacts of vinasse biogas replacing fossil oil for power generation, natural gas, and increasing sugarcane energy in Brazil. Renew Sustain Energy Rev. https://doi.org/10.1016/j.rser.2020.110281

Paes LAB, Bezerra BS, Deus RM, Jugend D, Battistelle RAG (2019) Organic solid waste management in a circular economy perspective – a systematic review and SWOT analysis. J Clean Prod 239:118086. https://doi.org/10.1016/J.JCLEPRO.2019.118086

Peterson E (2017) Is economic inequality really a problem? a review of the arguments. Social Sciences 6(4):147. https://doi.org/10.3390/soscs6040147

Pires A, Martinho G (2019) Waste hierarchy index for circular economy in waste management. Waste Manage 95:298–305. https://doi.org/10.1016/j.wasman.2019.06.014

Qerimi D, Dimitrievska C, Vasilevska S, Rrecaj AA (2020) Modeling of the solar thermal energy use in urban areas. Civil Engineering Journal 6(7):1349–1367

Ranta V, Aarikka-Stenroos L, Ritala P, Mäkinen SI (2018) Exploring institutional drivers and barriers of the circular economy: a cross-regional comparison of China, the US, and Europe. Resour Conserv Recycl 135:70–82

Reike KJ, D, Hekkert, M. (2017) Conceptualizing the circular economy: an analysis of 114 definitions. Resour Conserv Recycl 127:221–232

Ritzén S, Sandström GÖ (2017) Barriers to the circular economy–integration of perspectives and domains. Procedia Cirt 64:7–12

Saaty TL (1990) How to make a decision: The analytic hierarchy process. Eur J Oper Res 48:9–26

Sawhney A (2020) Striving towards a circular economy: climate policy and renewable energy in India. Clean Technologies and Environmental Policy 23:1–9

Shahbazi S, Wiktorsson M, Kurdve M, Jönsson C, Bjelkemyr M (2016) Material efficiency in manufacturing: Swedish evidence on potential, barriers and strategies. J Clean Prod 127:438–450

Sharma RK, Singh PK, Sarkar P, Singh H (2020) A hybrid multi-criteria decision approach to analyze key factors affecting sustainability in supply chain networks of manufacturing organizations. Clean Technol Environ Policy 22(9):1871–1889

Silafertruksa T, Gheewala SH (2020) Competitive use of sugarcane for food, fuel, and biochemical through the environmental and economic factors. The International Journal of Life Cycle Assessment 25(7):1343–1355

Silva C (2020) Montadoras e usinas se unem para tornar etanol soluções para reduzir emissões. O Estado de São Paulo. São Paulo, December 20, 2020. Economia, p., B10.

Singh RK, Kumar A, Garza-Reyes JA, de Sá MM (2020) Managing operations for circular economy in the mining sector: an analysis of barriers intensity. Resources Policy 69:101752

Sousa Jabbour ABL, Jabbour CJ, Sarkis J, Govindan K (2014) Brazil’s new national policy on solid waste: challenges and opportunities. Clean Technol Environ Policy 16(1):7–9

Trung TT (2020) Smart city and modelling of its unorganized flows using cell machines. Civil Engineering Journal 6(5):954–960

Wohlfahrt J, Fehlau F, Gabrielle B, Godard C, Kurek B, Joyce C, Theron O (2019) Characteristics of bioeconomy systems and sustainability issues at the territorial scale. A Review Journal of Cleaner Production 232:898–909. https://doi.org/10.1016/j.jclepro.2019.05.385

Yin RK (2003) Case study research: design and methods. (3). Beverly Hills, CA: Sage Publishing.

**Publisher’s Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
Authors and Affiliations

Gessica Mina Kim Jesus¹ · Daniel Jugend¹ · Luis Alberto Bertolucci Paes¹ · Regiane Máximo Siqueira¹ · Matheus Artioli Leandrin¹

Daniel Jugend
daniel.jugend@unesp.br

Gessica Mina Kim Jesus
gessica.min@unesp.br

Luis Alberto Bertolucci Paes
luis.paes@unesp.br

Regiane Máximo Siqueira
regiane.maximo@unesp.br

Matheus Artioli Leandrin
matheus.leandrin@gmail.com

¹ Production Engineering Department, Sao Paulo State University – UNESP, Av. Engenheiro Luiz Edmundo Carrijo Coube 14-01, PO BOX, Bauru, SP 17033-360, Brazil