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

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Research Article

Keywords: bioeconomy, developing countries, sustainable design, bioethanol, multi-criteria decision analysis.

Posted Date: May 3rd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-318975/v1

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.

1. 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. 2017). 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 CO_2 emissions (Qerimi et al. 2020).

Brazil is responsible for about 41% of 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 bio-fuel 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. 2021) 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. In Sect. 5, there is a discussion that integrates the results from case studies and AHP analysis. Section 6 presents the conclusions, limitations and suggestions for future research.

2. 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) defines 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. (2017), the CE can be understood as a business model that replaces the concept of end-of-life by reducing, 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. 2017), 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 (Ritzén 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, Ritzen 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 or 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, 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, technological and operational categories. A brief description of each barrier is presented, as well as its theoretical framework.

Table 1
Description of barriers to the adoption of the CE.

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 Upadhyay (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)

Categories	Barriers	Code	Description	Reference
	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 Upadhyay (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 Upadhyay (2020), Shahbazi et al. (2016), Garcia-Quevedo 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 e Upadhyay (2020), Shahbazi et al. (2016), Jabbour et al. (2020).

Categories	Barriers	Code	Description	Reference
	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 Upadhyay (2020), Shahbazi et al. (2016), Jabbour et al. (2020), Kapoor et al. (2020), Jabbour et al. (2020).

3. 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.

Table 2
Information on the case study companies.

	Company A	**Company B**
Foundation year	1946	Joint venture since 2010
Size	Large (3500 employees) 3 units in the state of São Paulo	Large (29,000 employees) 26 agro-industrial units in Brazil distributed in the states of São Paulo, Goiás and Mato Grosso
Industry and products	Sugarcane ethanol industry (sugar, ethanol, energy)	Sugarcane ethanol industry (sugar, ethanol, energy, distribution)
Production crop 2019/2020	Sugar (482 thousand tons), ethanol (530 thousand liters), electricity (511 thousand MWh)	Sugar (4.2 million tons), ethanol (2.5 billion liters), electricity (2.1 TWh)
Certifications	FSSC 22000, Bonsucro, RenovaBio, RFS2 (Renewable Fuel Standard), LCFS (Low Carbon Fuel Standard), METI, British Columbia, SMET, Greener Ethanol, Green Energy Seal	Bonsucro, RenovaBio, SMETA, EPA (USA), ISCC (Europe), METI (Japan), International REC Standard and California Air Resource Board

After initial contact, we collected the data through questionnaires with open questions, mainly about the CE practices in the companies and its 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 2013). Figure 1 shows the steps followed in the research method. 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 proposed by the research (see Table 1).
2. Measurement and data collection. Experts make their judgments by answering questions comparing two 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 two 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 was 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 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). SuperDecisions 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.

4. Results

4.1 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 3500 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 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."*

4.2 Company B

Company B is a multinational joint venture between a Brazilian and a Dutch company. The joint venture was made official in 2010, and this company has become one of the most competitive energy companies in the world. 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 Bonsucro, 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.

4.3 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 SuperDecisions 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.

Table 3
AHP weightings for barrier categories in Company A.

	Social and environmental	**Economic and financial**	**Technological and operational**	**Weighting**
Social and environmental	1	1/6	3	0.171
Economic and financial	6	1	7	0.751
Technological and operational	1/3	1/7	1	0.078

Table 4
AHP weightings for barrier categories in Company B.

	Social and environmental	Economic and financial	Technological and operational	Weighting
Social and environmental	1	1/9	1/3	0.066
Economic and financial	9	1	7	0.785
Technological and operational	3	1/7	1	0.149

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, technological and operational). For Company A, the social and environmental category was the second most significant, whereas for Company B, it was the third most significant. For Company B, the technological and operational category was the second most significant, whereas for Company A, it was the third most significant.

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).

Table 5
Local and global weightings for all barrier categories and specific barriers in Company A and B.

	Barrier	Local weightings		Global weightings	
Company		A	B	A	B
Social and environmental	BS1	0.179	0.293	0.030	0.019
	BS2	0.112	0.067	0.019	0.004
	BS3	**0.709**	**0.641**	0.121	0.042
Economic and financial	BEF1	**0.733**	0.078	**0.550**	0.061
	BEF2	0.067	0.171	0.050	0.135
	BEF3	0.199	**0.750**	0.150	**0.589**
Technological and operational	BTO1	**0.609**	**0.605**	0.048	0.090
	BTO2	0.071	0.115	0.005	0.017
	BTO3	0.187	0.115	0.014	0.017
	BTO4	0.133	0.166	0.010	0.025
Note: Values in bold are the highest weights					

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 10–90% 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 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.

5. Discussion

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 biowaste 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 sugar and alcohol 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 sugar and alcohol sector). The main barriers identified in order of priority were as follows:

1. Lack of financial We observed a lack of financial support for the adoption of CE in the qualitative and quantitative stages of this 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 The companies studied showed that they depend on investments in technologies to develop their current CE projects, such as bioenergy, biogas and solar 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 sugar and alcohol 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 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 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 CO_2 emissions through an efficient and environmentally responsible production process.

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.

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, lack of awareness and 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.

6. 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, which is important for the generation of renewable energy in Brazil. 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 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. Considering the Brazilian reality, 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 reuse of bio-waste. In this sense, public policy makers in Brazil's 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 can 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.

Finally, we recognize that this study has limitations that deserve consideration. First, even considering that the companies investigated stand out in the Brazilian sugarcane ethanol sector, the limitations of the research method we employed mean that the results presented here cannot be generalized. Second, 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 and identify other and new barriers to CE adoption. Future studies could also involve a greater number of industrial sectors and other stakeholders for the identification and prioritization of barriers to CE adoption. In addition, an investigation into how emerging countries such as Brazil address Nimby Syndrome could also guide future research on barriers to CE adoption.

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Figures

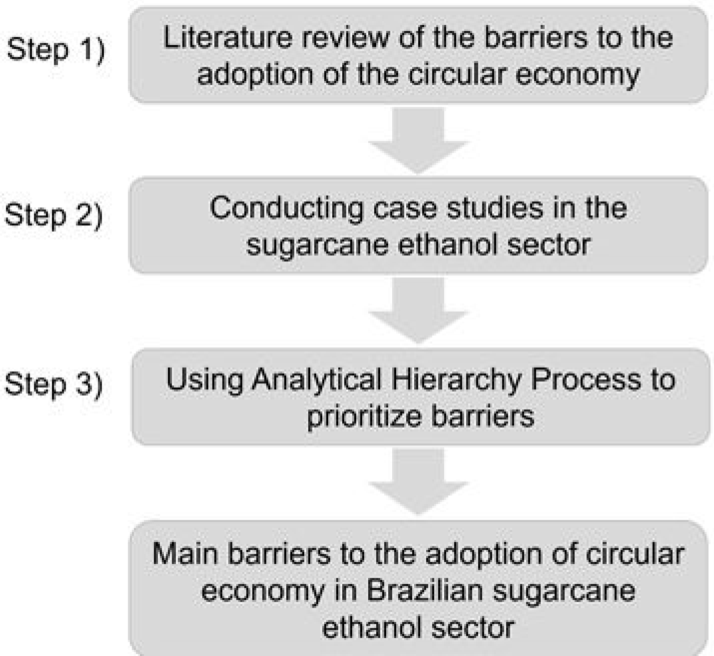

Figure 1

Research method steps.

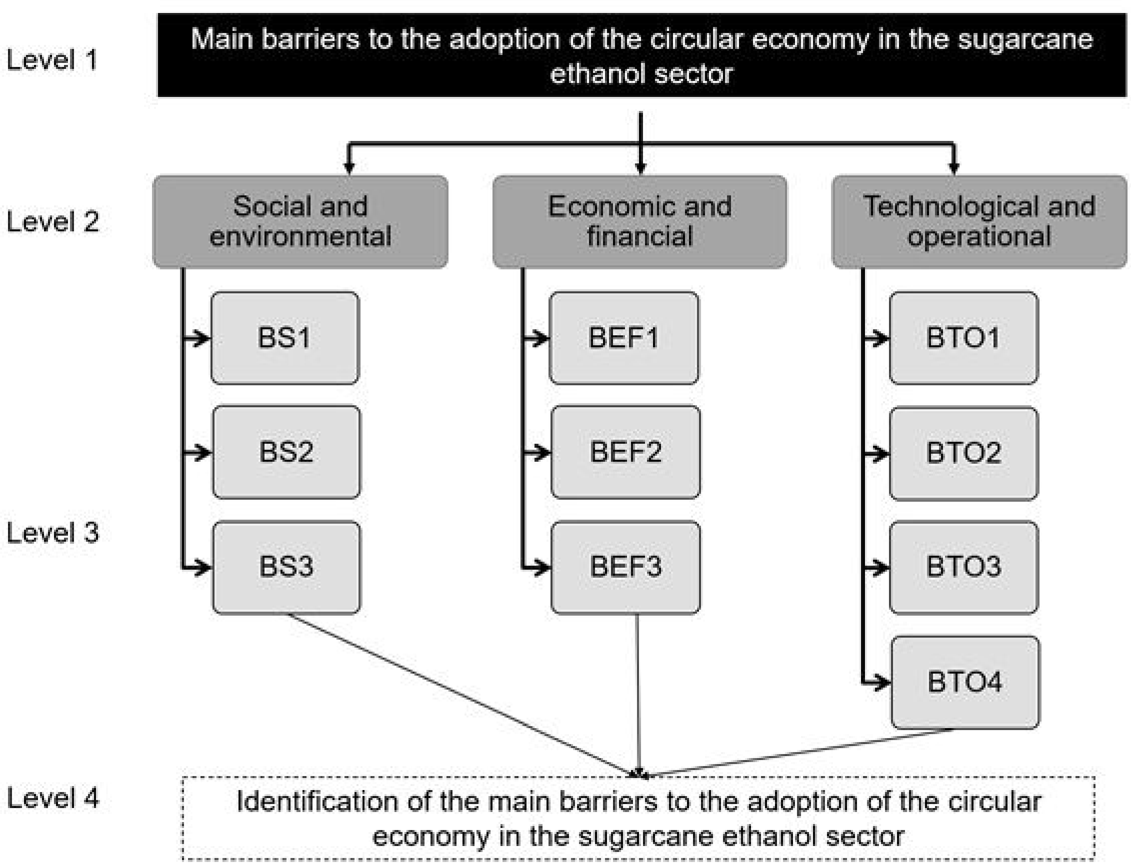

Figure 2

AHP structure for identifying barriers to adopting the CE in the sugarcane ethanol sector. Source: Adapted from Delmonico et al. (2018). Note: BS1 - lack of awareness of CE principles; BS2 - low demand for reused, remanufactured and shared products; BS3 - lack of regulation and legislation; BEF1 - lack of financial support and tax incentives; BEF2 - low cost of virgin materials; BEF3 - high cost of CE processes; BTO1 - lack of technology and equipment; BTO2 - lack of qualified labor; BTO3 - lack of design and production information; BTO4 - difficulty establishing partnerships in the supply chain.

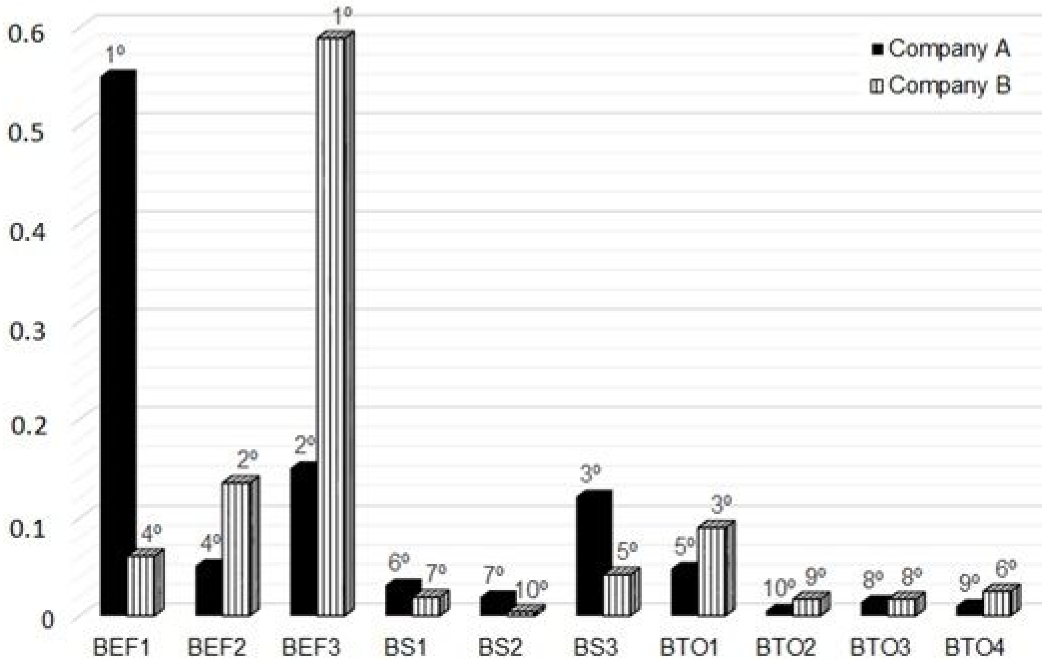

Figure 3

Global ranking of barriers to the CE in Companies A and B. Note: BS1 - lack of awareness of CE principles; BS2 - low demand for reused, remanufactured and shared products; BS3 - lack of regulation and legislation; BEF1 - lack of financial support and tax incentives; BEF2 - low cost of virgin materials; BEF3 - high cost of CE processes; BTO1 - lack of technology and equipment; BTO2 - lack of qualified labor; BTO3 - lack of design and production information; BTO4 - difficulty establishing partnerships in the supply chain.

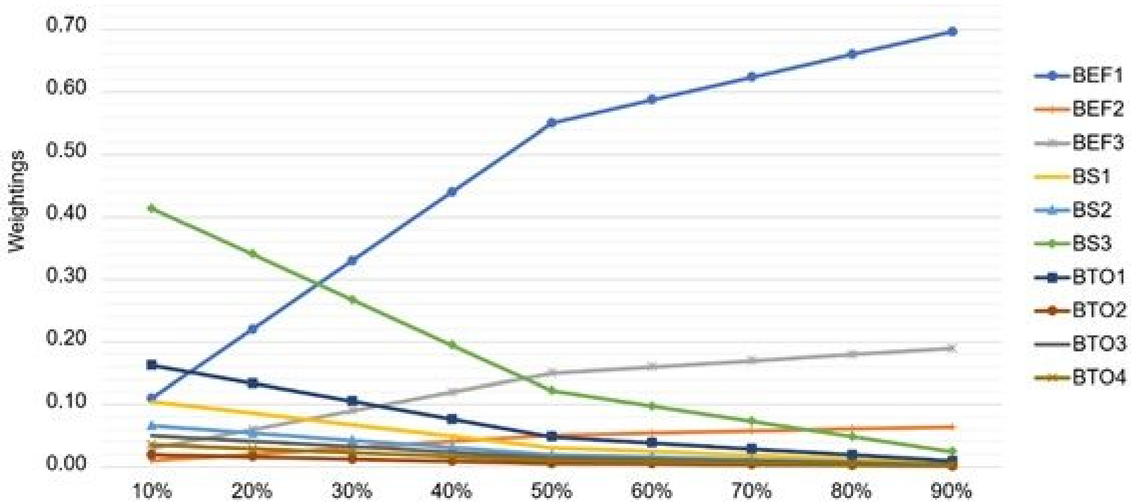

Figure 4

Ranking of specific barriers when the weightings for economic and financial category vary during sensitivity analysis for Company A. Note: BS1 - lack of awareness of CE principles; BS2 - low demand for reused, remanufactured and shared products; BS3 - lack of regulation and legislation; BEF1 - lack of financial support and tax incentives; BEF2 - low cost of virgin materials; BEF3 - high cost of CE processes; BTO1 - lack of technology and equipment; BTO2 - lack of qualified labor; BTO3 - lack of design and production information; BTO4 - difficulty establishing partnerships in the supply chain.

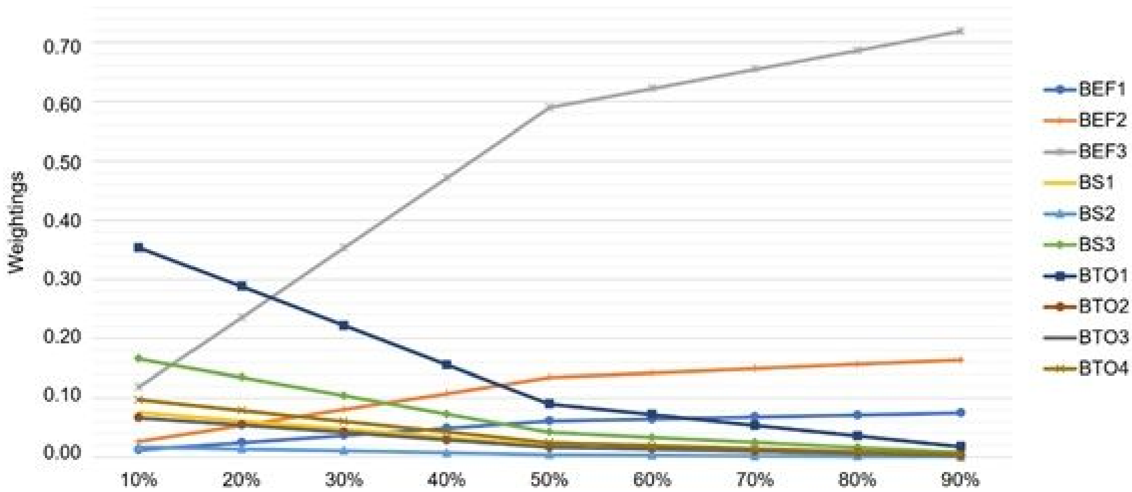

Figure 5

Ranking of specific barriers when the weightings for economic and financial category vary during sensitivity analysis for Company B. Note: BS1: lack of awareness of CE principles; BS2: low demand for reused, remanufactured and shared products; BS3: lack of regulation and legislation; BEF1: lack of financial support and tax incentives; BEF2: low cost of virgin materials; BEF3: high cost of CE processes; BTO1: lack of technology and equipment: BTO2; lack of qualified labor; BTO3: lack of design and production information; BTO4: difficulty establishing partnerships in the supply chain.