APPLICATION OF FUZZY TOPSIS FOR PRIORITIZING BARRIERS TO CIRCULAR ECONOMY ADOPTION IN THE AUTOMOTIVE SECTOR: A STUDY IN AN EMERGING COUNTRY

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ABSTRACT

Acknowledging the substantial economic, social, and environmental impacts of sustainability and circular economy (CE) practices, their imperative role in the automotive industry cannot be overstated. Despite this significance, there is a lack of studies addressing these critical themes within the automotive sector. This paper aims to bridge this gap by providing an examination of the barriers hindering the adoption of CE principles, with a specific focus on the Brazilian automotive industry. A survey, involving 41 experts comprising 21 academics specializing in sustainability and CE, 16 experienced managers, and 4 directors with substantial automotive industry expertise, was conducted. The study identified and evaluated 12 barriers to CE adoption in the automotive sector based on the experts' assessment using Fuzzy TOPSIS. The study's findings underscore the scarcity of professionals with sufficient knowledge and expertise), the absence of supportive public policies, and the inadequate commitment from leadership as the top three priority barriers. The research recommends targeted actions for companies, policymakers, and universities to collaboratively contribute towards overcoming these identified barriers and fostering a sustainable and circular trajectory for the automotive industry.

KEYWORDS

Fuzzy logic, Multicriteria decision making, Circular economy, Automotive industry, Barriers.

1. INTRODUCTION

In recent decades, the global landscape of industrial production has undergone a paradigm shift, necessitating a profound reconsideration of traditional economic models [1]–[3]. The imperatives of sustainable development have emerged as central tenets in this transformation, challenging organizations across diverse sectors to redefine their operational frameworks [1]. At the forefront of this evolution is the concept of the circular economy (CE), an innovative approach that seeks to decouple economic growth from resource depletion and environmental degradation [4]. In understanding the contextual nuances of sustainable development and CE, it becomes imperative to dissect the definitions and interconnections that underpin these fundamental concepts [5], [6].

Sustainable development, as articulated by the World Commission on Environment and Development (WCED), is development that meets the needs of the present without compromising the ability of future generations to meet their own needs [7]. In tandem, the CE builds upon this foundation, promoting a regenerative system where products, materials, and resources are perpetually cycled through value chains [8]. It aims to minimize waste, promote resource efficiency, and foster sustainable practices throughout the lifecycle of products [9]. As the global

community grapples with the ramifications of climate change and resource scarcity, the imperative for organizations to align with the principles of sustainable development and CE becomes increasingly pronounced [10].

Sustainability and CE principles are not confined to specific industries; rather, they represent a universal imperative for organizations of all types. The adoption of sustainable practices not only aligns with ethical considerations but also resonates with an evolving consumer base that prioritizes environmentally responsible products and services [4]. Beyond the ethical and consumer-driven motivations, integrating CE principles into organizational strategies can yield tangible economic benefits, including cost savings through resource efficiency and enhanced resilience to supply chain disruptions [11], [12].

Within the automotive sector, the stakes are particularly high as the industry navigates a complex terrain of technological innovation, regulatory pressures, and heightened environmental awareness [13]. The automotive sector's environmental footprint, driven by resource-intensive manufacturing processes and end-of-life vehicle disposal challenges, underscores the critical need for a transition to CE practices [13]. This paper explores the multifaceted importance of sustainability and CE principles within the automotive sector, shedding light on how embracing these concepts can catalyze innovation, foster resilience, and mitigate the industry's impact on the environment.

While the theoretical underpinnings of CE principles present a compelling vision for sustainable development, the translation of these ideals into practical implementation faces a myriad of challenges. Recognizing and understanding the barriers that impede the successful adoption of CE practices is a critical step in fostering meaningful change. In the context of the automotive sector, where the complexities of global supply chains and entrenched manufacturing practices prevail, comprehending and addressing these barriers becomes pivotal for effecting transformative change [4], [14].

Contemporary discourse surrounding the barriers to CE implementation reflects a nuanced understanding of the challenges faced by organizations in various sectors. Within the automotive industry, these challenges manifest in a spectrum ranging from technological constraints and economic considerations to regulatory hurdles and consumer behavior dynamics [6]. Despite the growing recognition of the importance of CE principles in fostering sustainability, there remains a noticeable gap in the existing body of literature concerning the specific challenges and barriers to implementing circular practices within the automotive sector. The automotive industry, with its intricate supply chains, complex manufacturing processes, and unique end-of-life considerations, represents a crucial arena for understanding and addressing barriers to circularity [10]. However, a limited number of studies have delved comprehensively into this domain. The scarcity of research on CE barriers in the automotive sector underscores the urgency for a more nuanced examination of the challenges that hinder the sector's transition toward a more sustainable and circular paradigm. Bridging this gap is essential for informed decision-making, strategic planning, and the development of effective policies that can drive meaningful change in the automotive industry's approach to CE practices.

The automotive industry holds paramount significance in emerging economies, serving as a key driver of economic growth, industrialization, and technological advancement [15], [16]. In these dynamic contexts, the automotive sector not only plays a pivotal role in job creation and income generation but also serves as a catalyst for fostering innovation and infrastructural development [17]. The industry's contributions extend beyond manufacturing, influencing ancillary sectors such as logistics, finance, and technology [18]. Additionally, the automotive sector serves as a barometer of a nation's industrial prowess and economic trajectory, reflecting the degree of

sophistication and global competitiveness attained by emerging economies [19]. As a major consumer of raw materials and a generator of substantial economic value, the automotive industry becomes a strategic focal point in the pursuit of sustainable development goals, necessitating a nuanced approach to integrating CE principles to address environmental concerns and promote long-term resilience [20], [21].

In this context, this study engages with current discussions on the barriers hindering the widespread adoption of CE practices within the automotive sector, particularly in emerging economies, aiming to provide insights that can inform strategic decision-making and policy formulation. In navigating the intricate intersection of sustainable development, CE principles, and the automotive sector, this paper aims to analyze the barriers to CE adoption in the automotive sector focusing on the Brazilian industry. By examining sector-specific challenges surrounding CE implementation, this study seeks to help managers and organizations in prioritizing and overcoming the barriers to enhance circularity in the automotive industry, especially for emerging countries.

2. THEORETICAL BACKGROUND

2.1. Circular Economy

The concept of a CE has gained substantial traction in academic literature and policy discussions over the past decade, reflecting a global shift toward sustainable and resource-efficient economic models [4], [5]. At its core, the CE seeks to decouple economic growth from the linear consumption of resources by emphasizing the principles of reuse, recycling, and regeneration. Literature on the CE is multifaceted, covering a range of disciplines including environmental science, economics, business management, and engineering.

Numerous studies highlight the environmental imperatives driving the adoption of CE principles. For instance, research by Geissdoerfer, et al. [4] underscores the potential of CE practices in reducing environmental impact and mitigating resource depletion. The shift toward circularity is seen as a response to the challenges posed by linear models, where the extraction, production, and disposal of goods contribute significantly to pollution and waste generation [9].

In the realm of business and management, scholars have explored the strategic implications of CE adoption. A study by Tukker (2015) emphasizes the potential economic benefits for businesses, including cost savings through resource efficiency and the development of new revenue streams through product-service systems. Additionally, circular business models are seen as a means to enhance resilience in the face of resource volatility [5], [9].

While the literature on the CE is expansive, there remains a notable gap in the understanding of barriers to its implementation, particularly in specific industries. Few studies have delved into the challenges faced by sectors such as the automotive industry in embracing CE practices [22], [23]. This gap becomes particularly apparent when considering the unique complexities of supply chains, manufacturing processes, and product life cycles within industries like automotive manufacturing [24]. Closing this research gap is crucial for informed decision-making and effective policy development, especially as industries navigate the transition toward more sustainable and circular practices.

The literature on the CE underscores its potential to address environmental concerns, generate economic benefits, and reshape business models. However, a more nuanced exploration of

industry-specific challenges, such as those within the automotive sector, is essential for advancing our understanding and facilitating the practical implementation of CE principles.

2.2. Circular Economy in the Automotive Sector

The application of CE principles within the automotive sector has emerged as a critical area of study, reflecting the industry's profound environmental impact and intricate product life cycles. While the broader literature on the CE provides a foundational understanding, a distinct body of research has evolved to specifically address the challenges and opportunities within automotive manufacturing [23], [25].

Exploring the environmental implications of conventional automotive manufacturing, recent research has delved into the sector's significant role in resource consumption and waste generation. The findings underscore the pressing need for interventions within the framework of a CE to address these environmental concerns [26], [27]. This suggests that a transition to circular practices could be instrumental in diminishing the ecological footprint of the automotive sector.
Within the economic domain, scholars have investigated the potential advantages of circular business models specific to the automotive industry. Their research highlights the positive impacts of remanufacturing, recycling, and product-service systems, not only in contributing to sustainability objectives but also in creating novel revenue streams and fortifying the sector's economic resilience [28].

Furthermore, the intricate supply chains inherent in the automotive industry present distinctive challenges to the implementation of CE principles, as discussed in earlier studies [24], [27], [29], [30]. These challenges underscore the importance of collaborative efforts among stakeholders to establish closed-loop systems, effectively managing material recovery and recycling across the entirety of the automotive value chain [31].

While extant literature provides valuable insights, few studies have undertaken a detailed examination of the complexities inherent in the industry, including technological constraints, regulatory issues, and consumer perceptions. Understanding and addressing these barriers are crucial for informing strategies that can facilitate the successful integration of circular practices in automotive manufacturing [20]. Thus, while the current literature provides foundational insights, there is a clear need for more targeted research addressing the unique complexities of the automotive sector to pave the way for effective CE implementation and sustainable practices within the industry.

2.3. Circular Economy in Emerging Economies

The discourse surrounding the CE has predominantly centered on developed economies [23], [32], [33], but an increasing body of literature is now exploring the application and challenges of circular practices in emerging countries [24], [25], [34]. These regions, characterized by rapid industrialization, growing populations, and dynamic economic landscapes, present a unique set of circumstances that influence the adoption and effectiveness of CE principles.

A study by Ajwani-Ramchandani et al. [35] provides insights into the role of CE in emerging economies, emphasizing the potential for sustainable development and resource efficiency. The authors argue that CE practices could offer emerging countries an avenue to decouple economic growth from environmental degradation, fostering long-term resilience.

In examining the challenges faced by emerging countries, Patwa et al. [36] shed light on the intricacies of implementing CE strategies in the context of developing economies. The study

emphasizes the need for tailored approaches that consider the socio-economic diversity and varying levels of industrialization present in emerging nations. These factors significantly impact the feasibility and effectiveness of circular practices.

Additionally, research by Khan and Haleem [37] delves into the policy landscape surrounding CE initiatives in emerging countries. The study highlights the critical role of government policies and regulations in shaping the adoption and success of circular practices. It underscores the importance of aligning regulatory frameworks with the specific socio-economic contexts of emerging nations to encourage widespread implementation.

The automotive sector, as a pivotal industry in many emerging countries, is not exempt from these considerations. Luthra et al. [38] and Khan et al. [39] address the challenges and opportunities of implementing CE principles in the automotive industry within emerging economies. Their work underscores the potential for circular practices to drive innovation, enhance resource efficiency, and contribute to sustainable development in these rapidly evolving contexts.

As emerging countries navigate the complexities of economic development and industrialization, the literature on CE in these regions highlights both the potential benefits and challenges. Tailoring CE strategies to the unique socio-economic and industrial landscapes of emerging nations is crucial for fostering successful implementation and realizing the sustainable development goals associated with circular practices.

3. METHODS

3.1. Structuring the Survey

The first stage of the study involved conducting a survey with academics and practitioners (managers and directors) with extensive experience in sustainability issues in the automotive sector to assess the incidence of difficulties. A total of 41 experts participated in the study, comprising 21 academics with a PhD in the field of sustainability and CE, 16 managers, and 4 directors with extensive experience in the automotive industry. All participants have knowledge about the Brazilian industrial landscape, particularly within the automotive sector. The average experience time of the experts was 16.1 years, with 73% having more than 10 years of experience.

The survey's structure was based on a literature review of barriers to CE in the automotive sector. The identified barriers were analyzed using the content analysis method proposed by Elo and Kyngäs [40], revealing convergence with the factors presented in Table 1.

Table 1. Barriers to circular economy in the automotive sector.

Code	Barrier	Description
B1	Inadequate leadership and management	Poor leadership and management can hinder the effective implementation of CE practices. This encompasses a lack of vision, strategy, and commitment from organizational leaders.
B2	Insufficient knowledge and expertise	The absence of necessary knowledge and expertise poses a challenge to the adoption of CE practices. Without trained professionals in sustainability principles, organizations may struggle to implement effective circular strategies.
B3	Challenges in	Difficulty in defining and communicating principles can

	articulating CE principles	impede CE adoption. Clarity is essential for aligning organizational efforts and understanding among stakeholders.
B4	Absence of awareness and perception	When there is a lack of understanding about the importance and benefits of CE practices, organizations and individuals may not be motivated to participate in CE initiatives.
B5	Inadequate eco-literacy among stakeholders	Limited understanding of CE concepts among stakeholders, including employees, partners, and customers, can hinder the successful implementation of circular practices.
B6	Absence of public policies supporting CE	Without supportive governmental policies, the transition to a CE may face regulatory obstacles and a lack of incentives. Policies play a crucial role in creating an enabling environment for circular initiatives.
B7	Perceived absence of a culture of sustainability in society	The perception that there is a lack of commitment to sustainability within society can impact organizational decisions to embrace circular practices. A supportive societal culture is instrumental in fostering sustainable behaviors.
B8	Lack of standards for assessing CE performance	The absence of universally accepted standards for evaluating CE performance makes it challenging to measure and compare the effectiveness of different circular strategies and initiatives.
B9	Elevated costs associated with CE processes	The high costs associated with transitioning to CE processes can be a significant barrier for organizations. Initial investments and operational adjustments may be perceived as financially burdensome.
B10	Ineffectual adoption of CE frameworks	If organizations fail to adopt and integrate CE frameworks effectively, the intended benefits may not be realized. This involves challenges in operationalizing circular strategies throughout the entire value chain.
B11	Restricted or underdeveloped access to information	Limited availability of relevant and comprehensive information about CE practices and opportunities can hinder informed decision-making and strategic planning.
B12	Absence of data integration	The lack of seamless integration of data related to circular practices can impede effective monitoring, reporting, and decision-making, hindering the optimization of CE initiatives.

Source: Elaborated by the authors based on Gopan and Balaji [19], Baldassarre et al. [16], Kayikci et al. [15], Yadav et al. [17], Kalverkamp and Raabe [32], and Rizvi et al. [18].

The barriers listed in Table 1 were use as a basis for developing the questionnaire for the survey. Experts were requested to evaluate each of these barriers considering the Brazilian automotive sector, using the following scale for their occurrence: "very low," "low," "medium," "high," or "very high." This scale was further transformed into a numeric score from 1 to 5, respectively.

3.2. Steps for the application of Fuzzy TOPSIS

The method employed to analyze the data collected was the Fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), which results from the combination of two well-established approaches: TOPSIS, developed by Hwang and Yoon [41], originally used for aiding decisions involving multiple criteria [42]–[45], and fuzzy logic, introduced by Chen [46], which incorporates the use of fuzzy numbers to represent linguistic variables. This is extended to Fuzzy TOPSIS, widely adopted in academic research across various areas [47]–[50].

In this study, respondents will assume the role of "criteria" in the application of Fuzzy TOPSIS, evaluated based on their ability to infer the presented issues. This approach has been used in studies such as those of Bobel et al. [51], Pompilio et al. [52] and Santos et al. [53]. The barriers under analysis were considered as the "alternatives." In this study, the application of the Fuzzy TOPSIS followed the steps proposed by Chen [46].

Firstly, the responses were synthesized into a matrix $\tilde{G}$ composed of vectors containing the scores in their fuzzy triangular form. The vector $\tilde{E}$ related to the levels of expertise assigned to each respondent was structured, with w corresponding to the level of expertise in its triangular fuzzy form.

$$\tilde{\mathbf{G}} = \begin{bmatrix} x_{11} & \cdots & x_{1m} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nm} \end{bmatrix} \qquad x_{ij} = [a_{ij}, \quad b_{ij}, \quad c_{ij}]$$

$$\tilde{E} = [\, w_1 \quad \ldots \quad w_n]$$

$$w = [w_1, \quad w_2, \quad w_3]$$

Following Chen's method (2000), the $\tilde{G}$ matrix was normalized by dividing all data by the highest score value, obtaining the matrix of normalized responses:

$$\mathcal{R} = [r_{ij}]_{mxn}, \; r_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right) \rightarrow C_j^* = \max(i)$$

Subsequently, the matrix $\mathcal{R}$ was weighted by the vector $\tilde{E}$, resulting in the matrix U:

$$U = [v_{ij}]_{mxn} \rightarrow i = 1, \; 2, \ldots, m; j = 1, 2, \ldots, n \rightarrow v_{ij} = r_{ij}\, w_j$$

Based on the matrix U, the distances of each element in relation to the positive ideal solution (A^*) and the negative ideal solution (A^-) were calculated as follows:

$$A^* = [v_1^*, v_2^*, v_3^*], \text{ where } v_j^* = [1,1,1]$$

$$A^- = [v_1^-, v_2^-, v_3^-], \text{ where } v_j^* = [0,0,0]$$

$$d(a,b) = \sqrt{\frac{1}{3}[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2]}$$

Thus, the total positive (d_i^*) and negative (d_i^-) distances for each parameter were calculated:

$$d_i^* = \sum_{j=1}^{n} d(v_{ij}, v_j^*) \; ; d_i^- = \sum_{j=1}^{n} d(v_{ij}, v_j^-)$$

Finally, the proximity coefficient (CC_i) was calculated serving as the basis to comparatively rank the analyzed barriers.

$$CC_i = \frac{d_i^-}{(d_i^* + d_i^-)}$$

4. RESULTS AND DISCUSSION

4.1. Ranking the Barriers to Circular Economy in the Automotive Sector

Based on the barriers mapped from the literature review and the proposed procedures of the Fuzzy TOPSIS method, a ranking was developed, as shown in Table 2.

Table 1. Barriers to circular economy in the automotive sector.

Barrier	CC_i	Ranking
B2	0.8110	1st
B6	0.7165	2nd
B1	0.6902	3rd
B8	0.6324	4th
B5	0.6111	5th
B4	0.5892	6th
B3	0.5555	7th
B7	0.4826	8th
B9	0.4711	9th
B10	0.4089	10th
B12	0.3987	11th
B11	0.3579	12th

In general, it is important to note that all barriers are significant and should be carefully considered by companies in the automotive sector and other institutions responsible for implementing CE, in particular, and sustainable practices more broadly.

In this study, however, for analytical purposes, Fuzzy TOPSIS is a highly useful tool for prioritizing these barriers based on expert evaluations. Thus, for the analysis, we consider the top 3 barriers (B2, B6 and B1) as high priority. For barriers ranked fourth to seventh (B8, B5, B4 and B3), we consider them of intermediate priority. As for those ranked from eighth to twelfth position (B7, B9, B10, B12 and B11), we consider them as lower priority barriers.

4.2. High Priority Barriers for the Automotive Industry in Adopting CE

Understanding the scarcity of professionals with sufficient knowledge and expertise (B2) emerges as a priority in addressing barriers to the successful implementation of CE practices within the automotive sector. The automotive industry is undergoing a transformative shift towards sustainability and circularity [15], [54], necessitating a workforce equipped with the requisite skills to navigate this transition [16]. Professionals knowledgeable about CE principles can play a pivotal role in developing and implementing sustainable practices, fostering innovation, and ensuring the integration of circular strategies throughout the automotive value chain [32]. The lack of such expertise poses a significant challenge, hindering the industry's ability to effectively adopt and optimize CE initiatives. In a sector where intricate supply chains, complex manufacturing processes, and innovative product life cycles are the norm, a skilled workforce becomes a linchpin for driving meaningful change. Addressing the knowledge gap is not just a matter of individual or organizational development; it is a strategic imperative for the automotive industry to thrive in a circular and sustainable future.

To overcome the barrier of a scarcity of professionals with sufficient knowledge and expertise in the implementation of CE practices in the automotive sector, a multifaceted approach is imperative. Firstly, educational institutions and industry associations should collaborate to develop specialized programs and workshops focused on CE principles tailored to the automotive sector. Offering targeted training and certifications will contribute to building a skilled workforce. Additionally, companies within the automotive industry should invest in continuous learning programs for their employees, fostering a culture of ongoing education and innovation. Partnerships between academia and industry could facilitate knowledge exchange, ensuring that academic insights align with practical industry needs [8]. Furthermore, establishing mentorship programs and knowledge-sharing platforms within the sector can accelerate the dissemination of CE knowledge [5], [11]. Ultimately, a concerted effort to bridge the knowledge gap will not only empower professionals but also position the automotive industry at the forefront of sustainable and circular practices.

Recognizing the absence of public policies supporting the CE (B6) as a pivotal barrier is crucial for understanding its profound impact on the automotive sector. Public policies serve as the bedrock for shaping the regulatory environment and providing incentives for sustainable practices. Without targeted policies to support circular initiatives, the automotive industry faces challenges in aligning its operations with circular principles, hindering the transition toward a more sustainable model [14], [21]. The lack of supportive policies not only slows down the adoption of circular practices but also introduces uncertainty into investment decisions and strategic planning, affecting everything from manufacturing processes to end-of-life considerations for vehicles [33], [55].

To overcome the barrier of the absence of public policies supporting the CE in the automotive sector, collaborative efforts between industry stakeholders and policymakers are paramount. Advocacy groups and automotive associations should actively engage with governmental bodies to advocate for the development and implementation of targeted policies that encourage CE practices. This collaboration can involve participating in policy discussions, providing industry insights, and emphasizing the positive environmental and economic impacts of circular initiatives [13]. Additionally, the automotive industry should take a proactive role in proposing policy frameworks that align with its sustainability goals. Building alliances with environmental organizations and fostering a dialogue with policymakers will contribute to the establishment of a supportive regulatory environment [8], [13], [56]. By actively participating in the policy-making process, the automotive sector can play a pivotal role in shaping a conducive landscape for circular practices, fostering innovation, and ensuring a sustainable future.

Understanding the barrier of inadequate leadership and support from top management (B1) is also considered of high importance in the context of adopting CE practices within the automotive sector. Leadership plays a central role in steering organizational strategies and fostering a culture of sustainability [57], [58]. When leadership lacks a commitment to and understanding of CE principles, it can significantly impede the successful implementation of sustainable practices throughout the automotive value chain [11]. This deficiency may result in a lack of resource allocation, insufficient motivation within the workforce, and an overall organizational inertia towards embracing circularity.

To overcome the barrier related to leadership and support from top management, proactive measures are crucial. Firstly, there is a need for targeted leadership training programs focusing on the principles and benefits of CE practices. These programs should be designed to enhance the understanding of top management about the strategic advantages of circularity and its long-term benefits for the organization. Additionally, incorporating CE goals into key performance indicators (KPIs) and performance evaluations for top management can create alignment and

accountability [58]. Encouraging the integration of CE principles into the overall organizational strategy, and ensuring that leadership actively communicates and reinforces the importance of sustainability, can foster a culture that supports the successful adoption of circular practices within the automotive sector.

4.3. Intermediate Priority Barriers for the Automotive Industry in Adopting CE

The absence of standardized metrics for evaluating CE performance in the automotive sector (B8) poses a significant impediment to its widespread adoption. Without universally accepted benchmarks, companies may struggle to measure and communicate their circular achievements effectively. This lack of clarity hampers decision-making, investment strategies, and the ability to demonstrate the tangible benefits of circular practices [18], [59]. To overcome this barrier, industry collaboration is crucial. Automotive stakeholders should engage in the development of standardized metrics, working alongside regulatory bodies, industry associations, and sustainability experts. Establishing clear performance indicators will not only enhance transparency but also provide a basis for comparison and continuous improvement within the sector.

The automotive industry's successful transition to CE practices relies heavily on the eco-literacy of its stakeholders (B5). From manufacturers to consumers, a lack of understanding about the environmental implications of various choices can impede the adoption of circular principles [4], [6], [8]. To address this barrier, comprehensive education and awareness initiatives are essential. Companies should invest in programs that enhance eco-literacy among employees, suppliers, and customers. This can include training sessions, informational campaigns, and the integration of sustainability education into industry events. By fostering a deeper understanding of the ecological impact of automotive processes and products, stakeholders can make informed decisions that contribute to the overall success of CE initiatives.

The absence of awareness and a positive perception of CE practices within the automotive sector (B4) can hinder widespread adoption. If key stakeholders, including consumers, suppliers, and industry leaders, lack understanding or hold negative perceptions about circular approaches, the industry may struggle to garner support. Overcoming this barrier requires strategic communication and advocacy efforts. Industry associations, manufacturers, and policymakers should collaborate on campaigns to raise awareness about the benefits of circular practices [11]. These efforts should highlight economic advantages, reduced environmental impact, and the long-term sustainability gains associated with CE initiatives. By actively shaping positive perceptions and enhancing awareness, the automotive sector can create a conducive environment for the adoption of circular practices.

Articulating CE principles effectively (B3) is vital for their successful integration into the automotive sector. Challenges in conveying these principles may lead to misunderstandings or resistance from stakeholders [10], [20], [34]. To overcome this barrier, industry-wide guidance and communication strategies are imperative. Companies should invest in clear and accessible communication materials that articulate the benefits, processes, and goals of circular practices. Additionally, fostering collaboration and open dialogue among stakeholders can address misconceptions and facilitate a shared understanding. Engaging in industry events, webinars, and forums to discuss and disseminate information about CE principles can contribute to a collective comprehension, paving the way for their seamless adoption within the automotive sector.

4.4. Lower Priority Barriers for the Automotive Industry in Adopting CE

The perceived absence of a culture of sustainability in society (B7) poses a challenge to the adoption of CE practices within the automotive sector. When consumers and stakeholders are not attuned to the importance of sustainable choices, there may be less demand for circular products or processes. This lack of societal alignment with sustainable values can impact market acceptance, making it essential to address perceptions [10], [20]. To overcome this barrier, comprehensive public awareness campaigns are necessary. Engaging with communities through educational initiatives, highlighting the environmental benefits of circular practices, and fostering a cultural shift towards sustainability can reshape perceptions. Collaborative efforts between the automotive industry, advocacy groups, and educational institutions can play a pivotal role in cultivating a societal ethos that supports and values CE principles.

The elevated costs associated with CE processes (B9) present an obstacle to their widespread adoption in the automotive sector. Circular practices often require upfront investments and operational changes that may initially increase costs [54]. This financial barrier can discourage companies from embracing circular initiatives. Overcoming this challenge involves a strategic approach to cost management. Governments, industry associations, and financial institutions can provide incentives such as tax breaks, subsidies, or low-interest loans to encourage the adoption of circular practices. Additionally, research and development efforts focused on cost-efficient circular technologies can contribute to making these processes more economically viable in the long run. Collaborative initiatives within the industry to share best practices for cost-effective circular strategies can further facilitate the sector's transition.

The ineffectual adoption of CE frameworks within the automotive sector (B10) hinders the integration of sustainable practices throughout the value chain. If companies struggle to implement circular principles cohesively, the potential environmental and economic benefits may remain unrealized. Overcoming this barrier requires a comprehensive approach to capacity building and knowledge dissemination. Industry-wide training programs, guidelines, and best practice sharing forums can empower businesses to effectively adopt CE frameworks [8]. Collaborations between industry leaders, researchers, and regulatory bodies can contribute to the development of standardized frameworks that streamline adoption. Continuous monitoring and evaluation mechanisms should be established to ensure the successful integration of circular principles and frameworks across diverse automotive operations.

The absence of data integration (B12) poses a challenge to the adoption of CE practices in the automotive sector. Seamless data integration is crucial for monitoring and optimizing circular processes, supply chain transparency, and overall performance assessment. Without integrated data, companies may struggle to track resource flows, measure environmental impacts, and make informed decisions [21]. To overcome this barrier, investment in advanced data management systems and technologies is essential. Companies should prioritize the integration of data systems across different stages of their operations, enabling real-time tracking and analysis. Collaborating with technology providers and fostering industry-wide standards for data interoperability can enhance the sector's ability to leverage data effectively, supporting the successful adoption of circular practices.

Restricted or underdeveloped access to information (B11) is also an important barrier to the adoption of CE practices within the automotive sector. Limited access to relevant data, research, and industry insights can impede informed decision-making and hinder the development of effective circular strategies [18], [59]. To overcome this barrier, collaborative efforts are crucial. Industry stakeholders should work together to create centralized repositories of information, share best practices, and facilitate knowledge exchange. Additionally, investment in research and

development initiatives focused on creating accessible databases and resources can enhance the sector's ability to access the information needed for informed decision-making. Partnerships between educational institutions, industry associations, and governmental bodies can further contribute to creating a knowledge-sharing ecosystem that supports the adoption of CE practices.

5. CONCLUSION

The identified barriers to the adoption of CE practices in the automotive sector underscore the complex challenges faced by the industry in its pursuit of sustainability. The scarcity of professionals with sufficient knowledge and expertise (B2), the absence of supportive public policies (B6) and the inadequate leadership commitment (B1) are key hurdles that demand a comprehensive and collaborative approach, and should be considered as priorities by organizations, policymakers, universities and other actors that compose the automotive industry. Addressing these barriers necessitates proactive initiatives, including specialized educational programs, advocacy for targeted policies, and leadership training. As the automotive industry undergoes a transformative shift towards circularity, bridging the knowledge gap, advocating for supportive policies, and fostering a sustainability-focused leadership culture are integral to navigating this transition successfully. By prioritizing these actions, the automotive sector can position itself at the forefront of sustainable and circular practices, contributing to a more resilient and environmentally responsible future.

Although not ranked in the top 3 by experts, the lack of standards for assessing performance (B8), inadequate eco-literacy among stakeholders (B5), absence of awareness and perception (B4) and challenges in articulating CE principles (B3) collectively impede the sector's transition toward sustainability. However, recognizing these challenges opens the door to targeted solutions. While these barriers present challenges, they also represent opportunities for collaboration and education. By prioritizing industry-wide initiatives, engaging in transparent communication, and investing in comprehensive education programs, the automotive sector can navigate these challenges effectively. The collaborative efforts of stakeholders, including regulatory bodies, industry associations, manufacturers, and consumers, are essential in creating a supportive environment that encourages the widespread adoption of circular practices. As the sector continues its journey toward sustainability, addressing these barriers will be instrumental in shaping a future where CE principles are seamlessly integrated into the fabric of the automotive industry.

While the perceived absence of a culture of sustainability (B7), elevated costs associated with circular processes (B9), ineffectual adoption of CE frameworks (B10), absence of data integration (B12) and restricted access to information (B11), are indeed important considerations, they fall lower in priority compared to the other barriers. Addressing these issues is crucial for fostering a comprehensive transition to CE practices within the automotive sector. However, the emphasis on public awareness campaigns, strategic cost management, capacity building, and technology integration should take precedence in the sector's sustainability agenda. Collaborative efforts between stakeholders, including the automotive industry, policymakers, and educational institutions, remain imperative to collectively overcome these barriers and pave the way for a more sustainable and circular automotive future.

Despite the insights gained from this research, it is essential to acknowledge certain limitations. Firstly, the study's findings are based on the perspectives of experts in sustainability and CE within the Brazilian automotive sector, and while their knowledge should be deemed important, the generalizability of the results to other industries or global contexts might be restricted. Additionally, the prioritization of barriers was determined based on their perceptions, and individual biases may have influenced the ranking. The study's cross-sectional design captures a

snapshot of the current state of the automotive industry's transition to circular practices in Brazil in the perspective of experts, but a longitudinal approach could offer a more dynamic understanding of evolving challenges. Furthermore, the research primarily focused on identifying barriers, and future studies could benefit from an in-depth exploration of successful strategies and best practices employed by companies that have effectively embraced CE principles. Lastly, the study did not extensively explore the potential interplay between regulatory frameworks and industry practices, warranting further investigation into the regulatory landscape's impact on the adoption of CE initiatives in the automotive sector.

In future research, it would be valuable to delve deeper into the nuanced interactions between the identified barriers to CE adoption in the automotive sector. Exploring the interconnectedness of these barriers and their cumulative impact on the industry's sustainability efforts could provide a more comprehensive understanding. Additionally, investigating the role of regional variations and cultural influences in shaping perceptions and responses to circular practices within the automotive sector could contribute valuable insights. Furthermore, longitudinal studies tracking the evolution of CE initiatives in the automotive industry over time would offer a dynamic perspective, enabling researchers to assess the effectiveness of implemented strategies and identify emerging trends. Integrating perspectives from diverse stakeholders, including consumers, suppliers, and regulators, could also enrich the research landscape, fostering a holistic understanding of the challenges and opportunities associated with the sector's transition to circularity.

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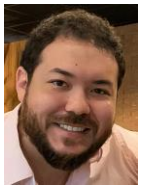

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